Life cycle analysis of transport modes

Final report
Volume I – LCA framework and findings

Prepared for
National Transport Development Policy Committee (NTDPC)

The Energy and Resources Institute

...towards global sustainable development

Suggested format for citation

T E R I. 2012

Final report - Life cycle analysis of transport modes (Volume I)

New Delhi: The Energy and Resources Institute. 84pp.

[Project code 2011UD02]

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Abbreviations[1]

AC	Alternating Current
AEI	Auroville Earth Institute
Al	Aluminium
AMC	Ahmedabad Municipal Corporation
APL	Aretefact Projects Ltd.
ARAI	Automotive Research Association of India
ASS	Annual Statistical Statements
B.G.	Broad Gauge
BEE	Bureau of Energy Efficiency (India)
BIS	Bureau of Indian Standards
BoQ	Bill of Quantities
BRTS	Bus Rapid Transit System
Btu	British thermal unit
CEA	Central Electricity Authority
CEPT	Center for Environmental Planning and Technology University
CO_2	Carbon dioxide
CS	Carbon Sequestration
CWR	Continuous Welded Rail
DBFOT	Design, Build, Finance, Operate and Transfer
DMRC	Delhi Metro Rail Corporation
ELV	End-of-Life Vehicles
ERC	Elastic Rail Clips
FRP	Fibre Reinforced Plastic

[1] Abbreviations for Volume I and II

g	gram
G.I.	Galvanized Iron
GHG	Greenhouse as
GIDB	Gujarat Infrastructure Development Board
GREET	Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation Model
HPEC	High Powered Expert Committee
HVAC	Heating, Ventilation, and Air Conditioning
HYSD	High Yield Strength Deformed (steel)
IRC	Indian Roads Congress
IRS	Indian Railway Standard Specification
KEPL	Kurukshetra Expressway Pvt. Ltd.
kg	kilogram
kJ	kilo joule
kl	kilo litre
km/kms	kilo metre
kV	kilo Volt
l	litre
lb	pound
LCA	Life Cycle Analysis
LDO	Light Diesel Oil
LPG	Liquefied Petroleum Gas
LWR	Long Welded Rail
m/mts	Metre
Mg	Magnesium
MIPS	Material Input Per Service unit

MMU	Mobile Maintenance Units
MoEF	Ministry of Environment and Forests (India)
MoRTH	Ministry of Road Transport and Highways (India)
MRTS	Mass Rapid Transit System
MS	Mild Steel
MUPB	Mobility-Umwelt-Belastungs-Punkte
NEWNE	Northern, Eastern, Western, and North-Eastern grid
NH	National Highway
NHAI	National Highway Authority of India
NHDP	National Highway Development Programme
NMV	Non-motorized vehicle
NR	Northern Railways
NRCO	Northern Railways Construction Organization
OMU	On-track Machines Unit
PDD	Project Design Document
PIU	Project Implementation Unit
PKM/PKT	Passenger kilometres travelled
PVC	Polyvinyl chloride
PWD	Public Works Department
RCC	Reinforced Cement Concrete
ROW	Right of Way
SIAM	Society of Indian Automobile Manufacturers
SRTU	State Road Transport Undertaking
T	tonne
TBM	Tunnel Boring Machine

TERI	The Energy and Resources Institute
TJ	Tera joule
UIC	International Union of Railways
UNFCCC	United Nations Framework Convention on Climate Change
USA	United States of America
vkm	Vehicle kilometre
WBM	Water Bound Macadam

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Executive summary

Environmental impact assessment exercises carried out to support decision-making in transport sector do not consider the full life cycle energy and CO_2 impacts of transport modes and focus on the tail pipe impacts only. It is, however, necessary that a holistic approach is adopted while analysing the impacts of the sector. Different transport modes involve varying degrees of construction and maintenance activities; while some modes may be highly material and energy intensive, the others may be comparably low intensive. Material and energy consumption at various stages of a transport project i.e. construction, operations and maintenance needs to be examined in order to fully understand its impacts on environment. Life cycle analyses (LCA) are typically used to assess such holistic/full-life impacts of various products, systems, projects, etc. ISO 14042 defines LCA as a systematic way of evaluating the environmental impacts of products or activities by following a 'cradle to grave' approach. It involves identification and quantification of material and energy consumption and emissions which affect the environment at all stages of the entire product life cycle.

LCA is considered to be a robust decision support tool due to the comparative character of the analysis performed in the LCA framework. It helps identify life stages of a product/system having maximum impact hence enabling identification of appropriate mitigation strategies.

Application of LCA to transport sector becomes important as transport impacts are not limited to tail-pipe only. Full life cycle impacts of transport need to be accounted and recognized while taking policy decisions related to 'greening' of the sector. The National Transport Development Policy Committee (NTDPC) established by the Government of India aims to understand the life cycle impacts in terms of energy consumption and CO_2 emissions associated with various life stages of different transport modes in order to make informed choices for climate-friendly and energy efficient modes for the country and for suggesting intra-mode improvements to reduce these impacts. In absence of any comprehensive LCA study for transport sector in India, NTDPC has commissioned a study to TERI focusing on establishing a robust India-specific methodology to estimate the life cycle impacts of transport modes in terms of energy consumption and CO_2 emissions and measuring these impacts for typical transport projects. The selected modes for this study include three urban transportation systems i.e. urban road, Bus Rapid Transit System (BRTS), and Metro Rail Transit System (MRTS) and two long-distance modes i.e. National Highway (NH), and long-distance passenger railway.

As stated earlier, all stages in the life cycle of a transport mode like construction of fixed infrastructure, manufacture of rolling stock, movement of rolling stock for transportation of people/goods, maintenance of rolling stock, maintenance of fixed infrastructure, etc. require material and energy consumption and lead to CO_2 emissions. The life cycle analysis proposed in this study takes into account all these life stages of transport modes. However, certain stages/activities have been left out/not included in the LCA system boundary in order to ensure that the proposed LCA methodology is doable. The system boundary defined in this study (tables 1 and 2) is in line with the several international applications of LCA in transport sector.

ISO 14000 framework for LCA and several papers[2] on methodology/application of LCA for transport sector were reviewed before drawing up a methodology for the proposed LCA exercise in this study. The key features of the LCA methodology developed by TERI are discussed below:

- The LCA framework drawn up by TERI is in line with the ISO 14000 framework for carrying out LCA studies. Most of the reviewed LCA methodologies for transport sector follow the ISO 14000 framework for LCA.

- The system boundary/scope of the LCA has been defined/limited. All LCA methodologies reviewed define the system boundaries and limit the scope of LCA in order to ensure that it is doable [Treloar et al. (2004), Mroueh et al. (2000), NTUA (2006)]. The system boundaries defined by TERI limit the scope of LCA to specific life stages and sub-stages of transport projects. The life stages/sub-stages considered by TERI are in consonance with the international LCA methodologies for transport sector. The life stages excluded by TERI are discussed below.
    - Material and energy consumption for manufacturing/constructing capital assets like the machinery used for construction, trucks used for transportation of materials, factories/industries/retail facilities used for manufacture/sale of construction materials, etc. are not included in the LCA scope on account of their expected insignificant contribution to a single project. The same is in line with the ISO 14000 framework and other LCA methodologies reviewed that also exclude such capital assets.
    - Demolition stage is not considered in the life cycle analysis as infrastructure projects in India are hardly demolished. This is in line with methodologies followed in various papers.

- TERI's LCA framework follows a bottom-up approach, wherein after the defining the system boundary, LCA is applied to specific projects by carrying out extensive data collection. Typical projects for all selected modes have been selected and studied in order to estimate the life cycle impacts. Similar approach is adopted in many transport sector LCA exercises e.g. Mroueh et al. (2000), Birgisdóttir (2005), NTUA (2006), Mroueh et al. (2001), etc.

- In most of the LCA applications reviewed, country-specific models have been developed to carry out the LCA. TERI has also developed its own India-specific spread sheet model to carry out LCA for transport sector.

The detailed scope/system boundaries defined for LCA are discussed in tables 1 and 2.

[2] Birgisdóttir (2005), Mroueh et al. (2000), Mroueh et al. (2001), Treloar et al. (2004), NTUA (2006), Chester (2008), Chester and Horvath (2009b), Chester et al. (2010), Stripple (1995) Stripple (2001), etc.

Table 1 Scope of LCA framework: Construction stage

Components of LCA	Included	Remarks
Production of construction materials		
Embodied energy and CO_2 of construction materials	√	India-specific coefficients from AEI (2009) International coefficient values from Hammond and Jones (2008)
Indirect energy consumption and CO_2 - Energy consumed for constructing buildings, manufacturing machinery, etc. used for production of materials	X	*Rational for not including* Capital assets - common infrastructure used for producing construction materials for several projects; Embodied energy cannot be included in one project
Transportation of construction materials		
Direct CO_2 due to fuel consumption by vehicles transporting construction materials	√	India-specific CO_2 emission factors from MoEF (2010) and ARAI (2007)
Embodied energy and CO_2 of fuel used	√	Indian and international coefficient values from TERI (2010) and Edwards et al (2006)
Embodied energy and CO_2 of trucks/vehicles used	X	Capital assets; common to several projects/non-construction activities
On-site impacts		
Direct CO_2 due to on-site fuel consumption (by construction machinery)	√	India-specific CO_2 emission factors: MoEF (2010) and ARAI (2007)
Embodied energy and CO_2 of fuel used (by construction machinery)	√	International coefficient values: TERI (2010); Edwards et al (2006)
Indirect energy consumption (energy consumed for manufacturing construction machinery/equipments used on site)	X	*Rational for not including* Machinery/equipments are common to several construction projects – need to proportionately distribute embodied energy to all projects where they are used – may not be significant per project
Vegetation removal - CS potential lost	√	Didn't need to calculate due to compensatory vegetation being planted
Vegetation removal - use of some portion of removed trees as fuelwood	√	Estimating the quantum of fuel wood from trees cut and then, applying its CO_2 emission factor

Table 2 Scope of LCA framework: Operations stage

Components of LCA	Included	Remarks
Direct energy consumption and CO_2 (tailpipe and embodied) emissions from vehicles moving on the transport corridor[3]	√	Energy consumed per passenger km estimated using actual fuel consumption data[4] for different modes; India-specific CO_2 emission factors used
Indirect energy consumption and CO_2 i.e. energy consumed and CO_2 emitted due to manufacturing and maintenance of rolling stock	√	Data estimated for USA considered
Maintenance of fixed infrastructure		
Activities associated with annual and periodic maintenance works: ▪ Material consumption (embodied energy and CO_2) ▪ Energy use on site	√ X	Only material consumption considered in maintenance activities. Energy efficiency levels in future assumed to remain same as today.

The LCA framework defined in tables 1 and 2 was used to estimate life cycle impacts of specific transport projects. The transport projects studied are listed in table 3. Due to limited time period of this study, TERI could not select a large sample of projects per mode to estimate the life cycle impacts. Hence, one typical project was selected per mode. TERI defined 'typical' projects as projects that do not have unusual features e.g. road and rail projects selected are in flat terrains, do not pass through forested areas, etc. As stated earlier, many international papers on LCA of transport also select typical projects to estimate life cycle impacts (Mroueh et al. (2000), Birgisdóttir (2005), NTUA (2006), etc.).

Table 3 Selected transport projects for which construction and maintenance data was collected and life cycle impacts were estimated

Mode	Construction projects studied	Maintenance projects studied
National Highway	Four laning of Rohtak-Bawal NH (NH-71)	Maintenance of Delhi-Agra NH
Long-distance rail	Construction of Rewari-Rohtak new line	Maintenance of Delhi-Bathinda line
Metro rail	Construction of Delhi Metro	Maintenance of Delhi Metro
BRTS	Construction of Ahmedabad BRTS	Maintenance of Ahmedabad BRTS
City road	Construction of a typical road in Delhi	Maintenance of a typical road in Delhi

[3] Due to limited time for this study, only one passenger vehicle type (car, bus, metro rail, long-distance train) has been studied per mode.
[4] Except in case of car

Conversion factors specifically embodied energy and CO_2 values of materials and fuels and tailpipe CO_2 emission factors of fuels are very critical for LCA analysis. India-specific values have primarily been used in this study to estimate energy and CO_2 impacts of material and fuel consumption. The study recognizes that technological and efficiency changes will take place in future which could reduce energy consumption and CO_2 in construction processes, materials production and transportation of materials. However, such efficiency improvements are not accounted while estimating the energy and CO_2 impacts for a 30 years period. It is assumed that the same level of efficiency will prevail for the 30 years period considered.

A spread sheet model has been developed to carry out the quantitative analysis. The results of life cycle impacts of the selected modes of transport considered in this study are summarized subsequently.

The application of the LCA methodology indicates that LCA is doable for transport projects. This is indeed the biggest contribution of the study. The study has contributed in shifting focus to life stages of transport projects (i.e. construction, maintenance, manufacture of rolling stock, etc.) that are usually ignored while assessing environmental impacts. The study is useful in two ways- it can help in choice of modes and in improvement within the modes.

The life cycle analysis carried out for typical transport projects using the proposed LCA methodology indicates that there are significant energy and CO_2 related impacts of transport systems throughout their life. Currently, the decision-making processes consider the energy and CO_2 impacts due to movement of rolling stock only, which gives an incomplete assessment of impacts. In addition to impacts due to rolling stock movement, there are significant energy and CO_2 impacts due to construction and maintenance of transport infrastructure. Construction and maintenance of transport infrastructure involves consumption of materials and fuels, some of which are highly energy and carbon intensive. LCA results indicate significant contribution of such materials and fuels to life cycle energy and CO_2 impacts of transport modes. Using alternative materials and fuels that are less energy and carbon intensive and are locally available can help reduce these impacts. Research studies on alternative materials and fuels should be conducted in order to identify energy efficient and low-carbon substitutes to conventional materials and fuels.

The results of this study show that an understanding of the full-life cycle energy and CO_2 impacts of transport modes can help choose modes or suggest inter-modal shift towards modes that are least energy and carbon intensive throughout their lives. In addition to choice of mode or promoting modal shift towards more ‘green’ modes, life cycle analysis can also help in intra-mode greening, as it helps understand the share of various components that contribute to energy consumption and CO_2 emissions, hence helping in identifying the appropriate mitigation measures. Some possible areas where energy reduction can be achieved during the life of a transportation system are:

- Reducing energy and CO_2 intensity of conventional materials used,
- Using alternative materials that are comparatively less energy and CO_2 intensive,
- Using locally available materials,
- Using energy efficient processes and machinery during construction and maintenance,

- Optimizing resource utilization during construction and maintenance, especially for transportation of materials (using locally available materials, reducing idling, using rail for bulk transport of materials, etc.),
- Promoting inter-modal shift (towards more energy efficient modes),
- Improving efficiency of rolling stock, and
- Reducing energy and material intensity during manufacturing and maintenance of rolling stock.

The study findings also indicate that if life of projects is enhanced, then the energy and CO_2 impacts due to re-construction can be reduced/deferred, especially in the case of road-based projects that tend to have shorter life. Life of the projects can be enhanced by continued maintenance. Maintenance of constructed assets should hence be given due importance; it will help reduce both monetary and environmental costs on a life cycle basis.

As stated earlier, traditional environmental impact analysis exercises carried out to support decision-making in transport sector do not consider the full life cycle energy and CO_2 impacts of transport modes. It is important that decisions related to choice of transport modes consider the life cycle impacts in terms of energy and CO_2 emissions in addition to other financial, technical, and environmental criteria used today.

In addition to financial and technical feasibility and environmental impact assessment exercises carried out at project selection/development stage, LCA estimating energy and CO_2 impacts should also be carried out. As stated earlier, this study has sought to establish a robust methodology to estimate the life cycle impacts. Further work is necessary to fine-tune the methodology and adapt it for use on a continuous basis for taking informed investment decisions. The successful use of the methodology will depend on the data available and data availability is a challenge in India. Database should be constructed to support the LCA.

Hence, to be able to use LCA in transport sector decision making, research and supporting database creation should be encouraged and supported by the government.

Summary of the key results of the study

Table 1 Summary of LCA results for transport modes studied

	Phase	Embodied energy	Unit	Embodied CO_2	Unit	Remarks
National Highway (4-lane with service road)						
Fixed infrastructure	Construction	39.1	TJ/km	3,442.4	T/km	India-specific values, Based on TERI's analysis
	Maintenance (30years)	27.8	TJ/km	1,072.9	T/km	
Rolling stock	Manufacture	1.7	TJ/bus*	140.0	T/bus[5]	USA-specific values, Source: Chester and Horvath (2009b)
	Maintenance (full life)	0.3	TJ/bus*	22.0	T/bus	
	Operations (long-distance bus; diesel)	221.9	kJ/PKM	17.9	g/PKM	India-specific values, Based on TERI's analysis
Long-distance rail (single line)						
Fixed infrastructure	Construction	12.0	TJ/km	1,294.3	T/km	India-specific values, Based on TERI's analysis
	Maintenance (30years)	20.1	TJ/km	1,892.2	T/km	
Rolling stock	Manufacture	5.0	TJ/coach	300.0	T/coach	USA-specific values, Source: Chester and Horvath (2009b)
	Maintenance (full life)	4.2	TJ/coach	183.3	T/coach	
	Operations (diesel traction)	107.6	kJ/PKM	8.7	g/PKM	India-specific values, Based on TERI's analysis
	Operations (electric traction)	50.7	kJ/PKM	11.4	g/PKM	

[5] Diesel bus

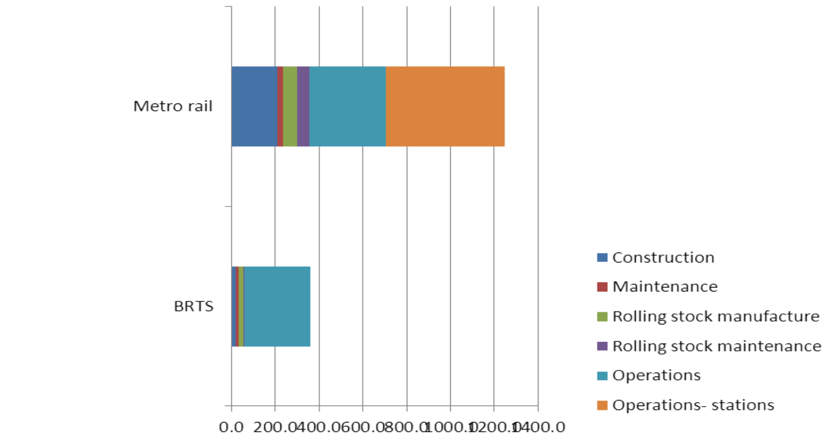
	Phase	Embodied energy	Unit	Embodied CO_2	Unit	Remarks
BRTS (ROW ranging from 25 to 60m)						
Fixed infrastructure	Construction					India-specific values, Based on TERI's analysis
	1 km corridor	51.7	TJ/km	2698.4	T/km	
	1 km bus lanes only	12.3	TJ/km	371.7	T/km	
	1 bus stop	3.6	TJ/stop	346.8	T/stop	
	Maintenance[6] (30years)					
	1 km corridor	65.3	TJ/km	2,449.2	T/km	
	1 km bus lanes only	16.0	TJ/km	446.0	T/km	
Rolling stock	Manufacture	1.7	TJ/bus[7]	140.0	T/bus	USA-specific values, Source: Chester and Horvath (2009b)
	Maintenance (full life)	0.3	TJ/bus[8]	22.0	T/bus	
	Operations 2012 (AC diesel bus)	544.1	kJ/PKM	44.6	g/PKM	India-specific values, Based on TERI's analysis
	Operations 2014 (AC diesel bus)	458.1	kJ/PKM	36.9	g/PKM	
Metro rail (double track)						
Fixed infrastructure	Construction (1 km metro line and 1 station)	245.1	TJ/km	23,246.1	T/km	India-specific values, Based on TERI's analysis
	Maintenance (30years)[9]	8.8	TJ/km	792.0	T/km	
Rolling stock	Manufacture	2.2	TJ/coach	130.0	T/coach	USA-specific values, Source: Chester and Horvath (2009b)
	Maintenance (full life)	1.8	TJ/coach	81.0	T/coach	
	Operations	86.4	kJ/PKM	19.7	g/PKM	India-specific values, Based on TERI's analysis

[6] Only maintenance of corridor considered; maintenance of station not included.
[7] Diesel bus
[8] Diesel bus
[9] Maintenance of station not included

	Phase	Embodied energy	Unit	Embodied CO_2	Unit	Remarks
City road (6-lane with service road)						
Fixed infrastructure	Construction	31.3	TJ/km	2439.5	T/km	India-specific values, Based on TERI's analysis
	Maintenance (30years)	72.8	TJ/km	4594.3	T/km	
Rolling stock	Manufacture	0.10 0.12	TJ/car (petrol) TJ/car (diesel)	8.50 9.80	T/car (petrol) T/car (diesel)	USA-specific values, Source: Chester and Horvath (2009b)
	Maintenance (full life)	0.04 0.04	TJ/car (petrol) TJ/car (diesel)	3.30 3.30	T/car (petrol) T/car (diesel)	
	Operations	1870.0 2343.3 2293.3 467.5	kJ/PKM (petrol car) kJ/PKM (diesel car) kJ/PKM (CNG car) kJ/PKM (two-wheeler)	146.0 188.6 138.1 36.5	g/PKM (petrol car) g/PKM (diesel car) g/PKM (CNG car) g/PKM (two-wheeler)	India-specific values, Based on TERI's analysis

The LCA results derived in the study have been applied to the Ahmedabad BRTS[10] and Delhi metro rail (phase I and II) projects to estimate per PKM and per km energy consumption and CO_2 emission values for the full life cycle of these projects. The results are shown in figures 1 to 4.

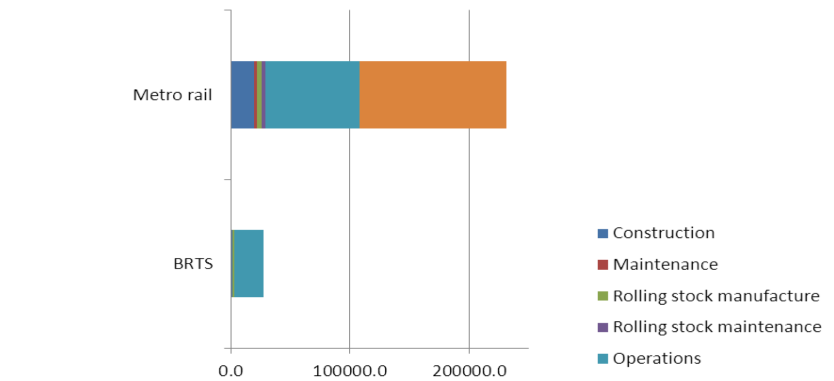
Figure 1 Life cycle energy consumption (per km) - Ahmedabad BRTS and Delhi metro rail (phase I and II) projects



	BRTS	Metro rail
Construction	19.3	209.7
Maintenance	16.0	26.4
Rolling stock manufacture	19.4	65.8
Rolling stock maintenance	3.1	55.9
Operations	301.0	348.9
Operations- stations	0.0	538.9

TJ/KM

Figure 2 Life cycle CO_2 emissions (per km) - Ahmedabad BRTS and Delhi metro rail (phase I and II) projects

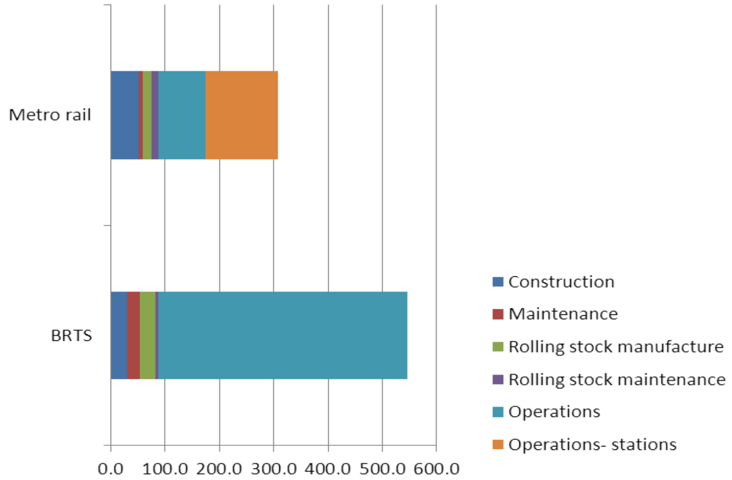


	BRTS	Metro rail
Construction	1041.2	19912.9
Maintenance	446.0	2376.0
Rolling stock manufacture	1600.0	3946.7
Rolling stock maintenance	251.4	2466.7
Operations	24228.0	79468.7
Operations- stations	0.0	122742.8

CO_2 - T/KM

[10] Total BRTS project in Ahmedabad (129 km), which is expected to be fully operational by 2014 has been considered. The system has been assumed to run to its full capacity. Only bus lanes have been considered for the construction and maintenance components.

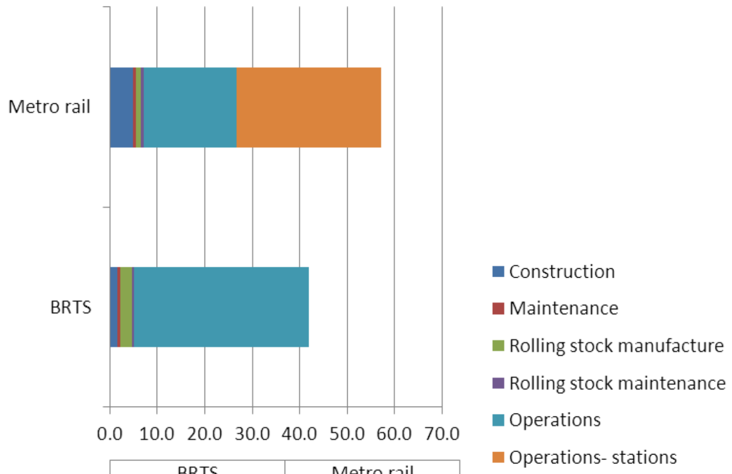
Figure 3 Life cycle energy consumption (per PKM) - Ahmedabad BRTS and Delhi metro rail (phase I and II) projects



	BRTS	Metro rail
Construction	29.3	51.9
Maintenance	24.4	6.5
Rolling stock manufacture	29.6	16.3
Rolling stock maintenance	4.7	13.8
Operations	458.1	86.4
Operations- stations	0.0	133.4

Energy - kJ/PKM

Figure 4 Life cycle CO_2 emissions (per PKM) - Ahmedabad BRTS and Delhi metro rail (phase I and II) projects



	BRTS	Metro rail
Construction	1.6	4.9
Maintenance	0.7	0.6
Rolling stock manufacture	2.4	1.0
Rolling stock maintenance	0.4	0.6
Operations	36.9	19.7
Operations- stations	0.0	30.4

CO_2 - g/PKM

The following figures summarize the LCA results for different life stages of the selected modes of transport.

Figure 5 Embodied energy per km: Results for construction and maintenance stages

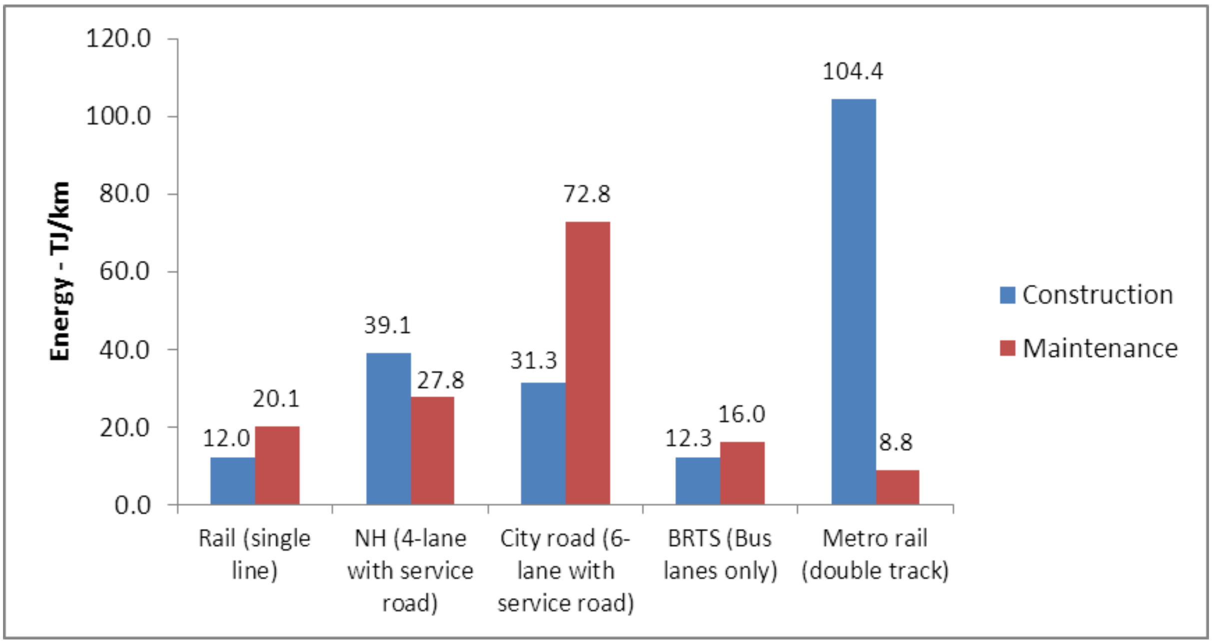


Figure 6 Embodied CO_2 emissions per km: Results for construction and maintenance stages

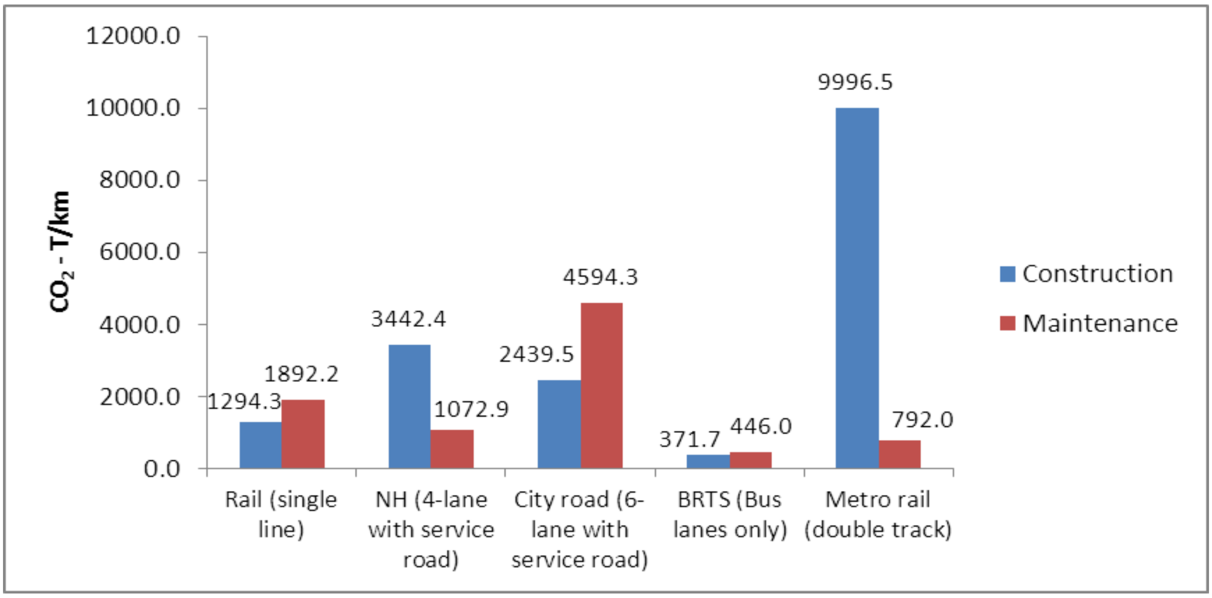


Figure 7 Embodied energy of rolling stock

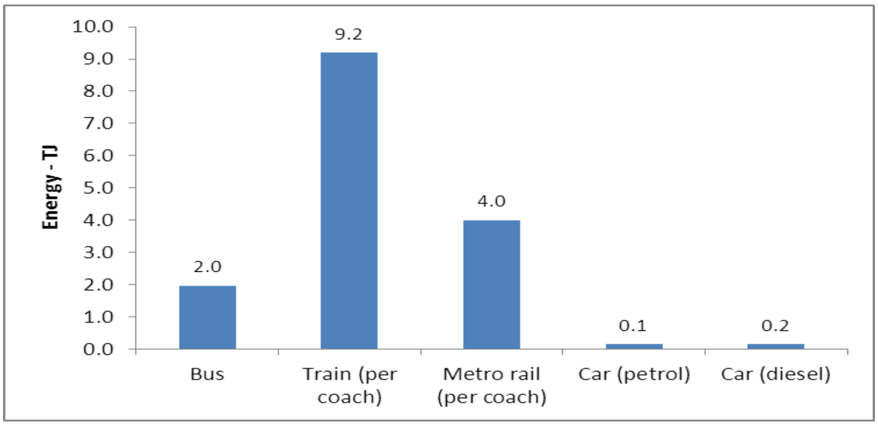


Figure 8 Embodied CO_2 of rolling stock

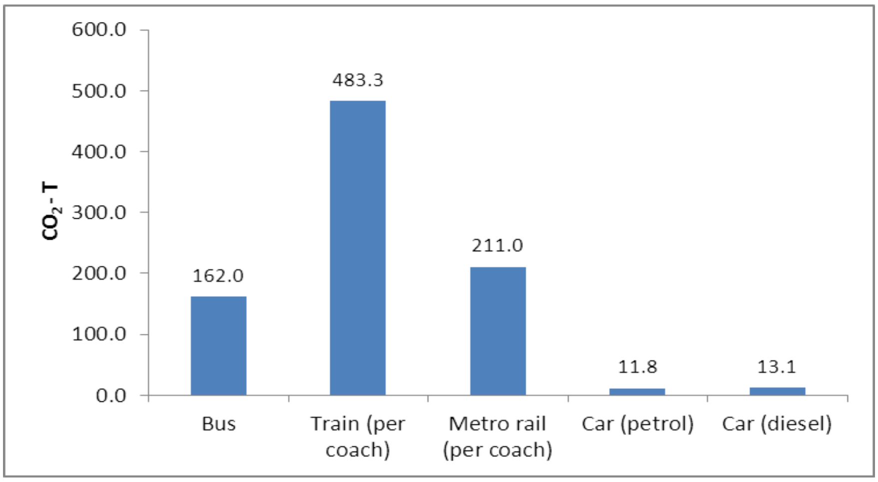


Figure 9 Operational energy consumption (kJ/PKM)

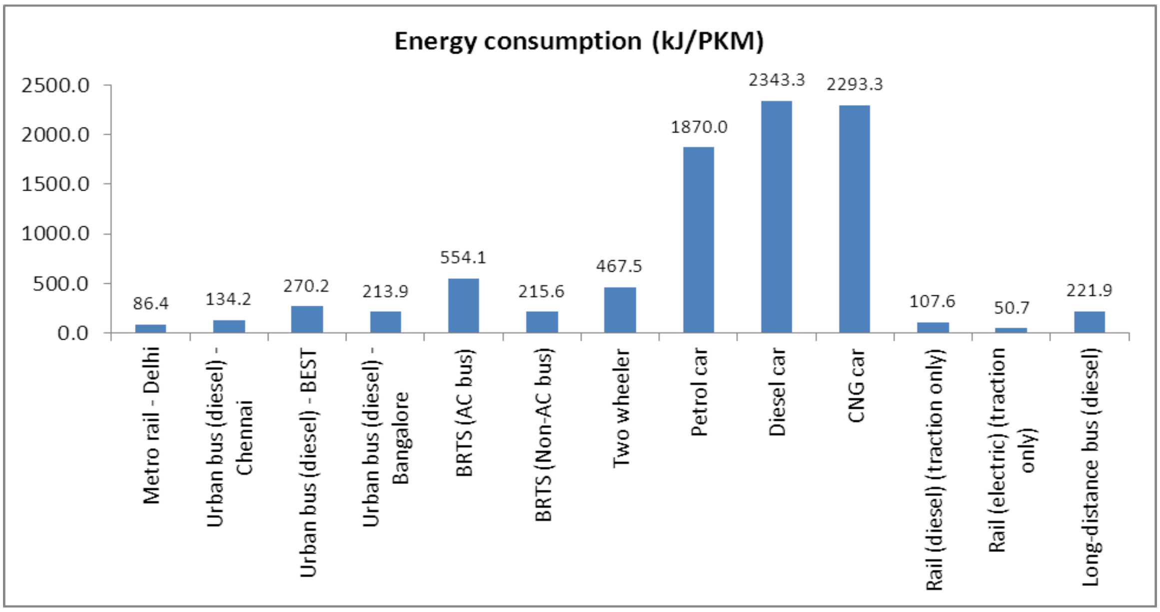
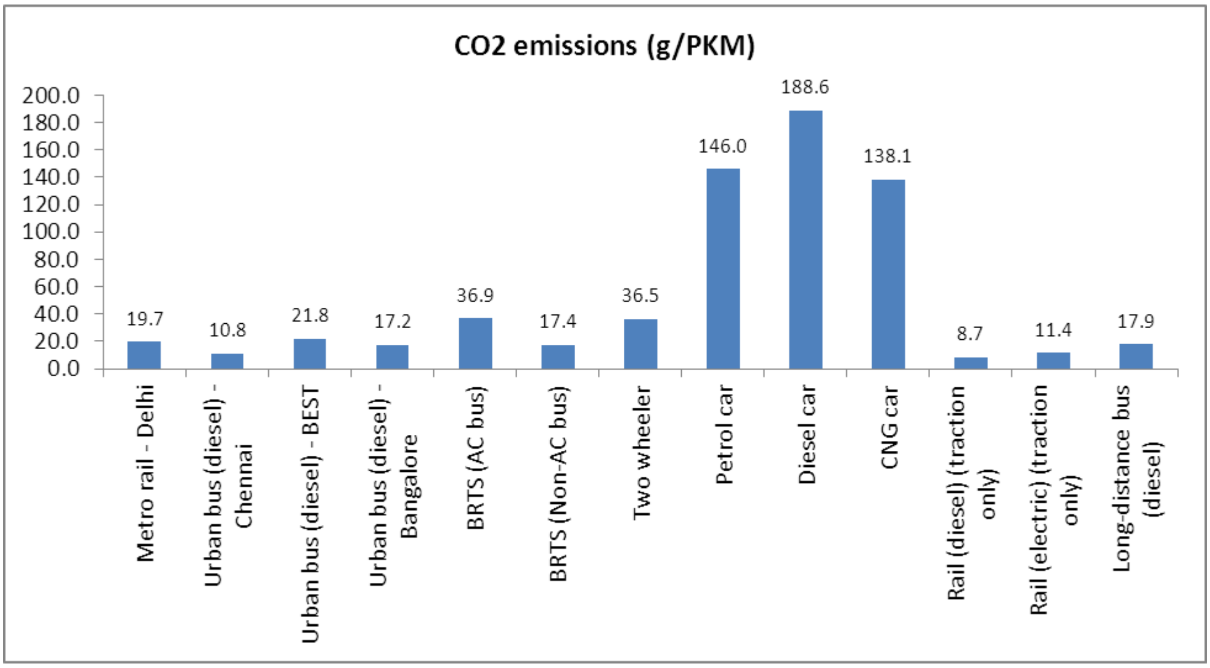


Figure 9 Operational CO_2 emissions (g/PKM)



It should be noted that the LCA methodologies, approach and results for all countries will vary on account of several reasons like differences in construction technologies, use of materials, embodied energy and carbon factors, fuel emission factors, level of efficiency, etc. It is hence not appropriate to compare the LCA results derived for other countries with the Indian results derived in this study. TERI has hence not attempted to compare results with any international studies. Ideally, the results should be compared with LCA exercises for the same country; LCA methodology, system boundary should be same for the compared projects. Due to absence of any such study for India, TERI cannot compare the results derived in this study with any other study.

Chapter 1: About the study and approach adopted

1.1 Background

Environmental impact assessment exercises carried out to support decision-making in transport sector do not consider the full life cycle energy and CO_2 impacts of transport modes and focus on the tail pipe impacts only. It is, however, necessary that a holistic approach is adopted while analysing the impacts of the sector. Different transport modes involve varying degrees of construction and maintenance activities; while some modes may be highly material and energy intensive, the others may be comparably low intensive. Material and energy consumption at various stages of a transport project i.e. construction, operations and maintenance needs to be examined in order to fully understand its impacts on environment. Life cycle analyses (LCA) are typically used to assess such holistic/full-life impacts of various products, systems, projects, etc. ISO 14042 defines LCA as a systematic way of evaluating the environmental impacts of products or activities by following a 'cradle to grave' approach. It involves identification and quantification of material and energy consumption and emissions which affect the environment at all stages of the entire product life cycle.

LCA is considered to be a robust decision support tool due to the comparative character of the analysis performed in the LCA framework. It helps identify life stages of a product/system having maximum impact hence enabling identification of appropriate mitigation strategies.

Application of LCA to transport sector becomes important as transport impacts are not limited to tail-pipe only. Full life cycle impacts of transport need to be accounted and recognized while taking policy decisions related to 'greening' of the sector. The National Transport Development Policy Committee (NTDPC) established by the Government of India aims to understand the life cycle impacts in terms of energy consumption and CO_2 emissions associated with various life stages of different transport modes in order to make informed choices for climate-friendly and energy efficient modes for the country and for suggesting intra-mode improvements to reduce these impacts. In absence of any comprehensive LCA study for transport sector in India, NTDPC has commissioned a study to TERI focusing on establishing a robust India-specific methodology to estimate the life cycle impacts of transport modes in terms of energy consumption and CO_2 emissions and measuring these impacts for typical transport projects. The selected modes for this study include three urban transportation systems i.e. urban road, Bus Rapid Transit System (BRTS), and Metro Rail Transit System (MRTS) and two long-distance modes i.e. National Highway (NH), and long-distance passenger railway.

1.2 Objectives of the study

- Establish a robust LCA methodology to compare different modes of transport on the basis of their life cycle impacts in terms of energy consumption and CO_2 emissions
- Use the LCA methodology to estimate the life cycle energy consumption and CO_2 emission values for the different modes of transport

1.3 Methodology, system boundaries and approach adopted for estimating life cycle energy and CO_2 impacts

All stages in the life cycle of a transport mode like construction of fixed infrastructure and production of materials used in construction, manufacture of rolling stock, movement of rolling stock for transportation of people/goods, maintenance of rolling stock, maintenance of fixed infrastructure, etc. require material and energy consumption and lead to CO_2 emissions. The life cycle analysis proposed in this study takes into account all these life stages of transport modes. However, certain stages/activities have been left out/not included in the LCA system boundary in order to ensure that the proposed LCA methodology is doable. The detailed scope/system boundaries of LCA and approach adopted for estimating life cycle energy and CO_2 impacts of the selected modes of transport are discussed in this section. The system boundary defined in this study is in line with the several international applications of LCA in transport sector.

1.3.1 LCA methodology

ISO 14000 framework for LCA and several papers on methodology/application of LCA for transport sector were reviewed before drawing up a methodology for the proposed LCA exercise in this study. The key features of the LCA methodology developed by TERI are discussed below:

- The LCA framework drawn up by TERI is in line with the ISO 14000 framework for carrying out LCA studies. Most of the reviewed LCA methodologies for transport sector follow the ISO 14000 framework for LCA [(Birgisdóttir (2005), Mroueh et al. (2000), Mazri et al., (year unknown)].
- The system boundary/scope of the LCA has been defined/limited. All LCA methodologies reviewed define the system boundaries and limit the scope of LCA in order to ensure that it is doable [Treloar et al. (2004), Mroueh et al. (2000), NTUA (2006)]. The system boundaries defined by TERI limit the scope of LCA to specific life stages and sub-stages of transport projects. The life stages/sub-stages considered by TERI are in consonance with the typical LCA methodologies for transport sector. TERI has considered construction, maintenance and operations life stages and their key sub-stages. The key stages that are included are:
    - Raw material extraction, processing, transport and manufacture
    - Transportation of construction materials/waste to and from construction site
    - On-site energy usage
    - Consumption of materials for annual and periodic maintenance
    - Material and energy consumption for manufacture and maintenance of rolling stock
    - Direct energy consumption for rolling stock operations

  The material and energy consumption for manufacturing/constructing capital assets like the machinery used for construction, trucks used for transportation of materials, factories/industries/retail facilities used for manufacture/sale of construction materials, etc. are not included in the LCA scope on account of their expected insignificant contribution to a single project. The same is in line with the ISO 14000 framework and other LCA methodologies reviewed that also exclude such capital assets; none of the reviewed LCA methodologies included capital assets.

Demolition stage is not considered in the life cycle analysis as infrastructure projects in India are hardly demolished. This is in line with methodologies followed in various papers:

  - Demolition stage is not included in Mroueh et al. (2000) and NTUA (2006)
  - Inclusion of demolition stage is optional in Birgisdóttir (2005)
  - While Stripple (2001) indicates inclusion of *disposal/reuse of the road at the end of the life cycle*, it also indicates *that most roads have no final end. Instead they are reconstructed or replaced by a new road while the old road remains in operation.*

- TERI's LCA framework follows a bottom-up approach, wherein after the defining the system boundary, LCA is applied to specific projects by carrying out extensive data collection. Typical projects for all selected modes have been selected and studied in order to estimate the life cycle impacts.[11] Due to limited time period for this study, TERI could not select a large sample of projects per mode to estimate the life cycle impacts. Hence, one typical project was selected per mode. TERI defined 'typical' projects as projects that do not have unusual features e.g. road and rail projects selected are in flat terrains, do not pass through forested areas, etc. Many international papers on LCA of transport also select typical projects to estimate life cycle impacts (Mroueh et al. (2000), Birgisdóttir (2005), NTUA (2006), Mroueh et al. (2001), etc.).
- In most of the LCA applications reviewed, country-specific spread sheet models/ software programs have been developed to carry out the LCA. TERI has also developed its own India-specific spread sheet model to carry out LCA for transport sector.
  - ROAD-RES model (software model), a new life cycle assessment model for road construction and disposal of residues in Denmark developed in Birgisdóttir (2005)
  - Spread sheet model for carrying out LCA for roads with conventional materials in Sweden developed in Stripple (1995) and Stripple (2001)
  - Spread sheet model for LCA of roads in Finland developed in Mroueh et al. (2000) and Mroueh et al. (2001)
  - Treloar et al. (2004) have developed LCA model for Australia
  - Chester (2008), Chester and Horvath (2009b), and Chester et al. (2010) also develop their own models for carrying out LCA for transport modes in U.S.A
- All reviewed papers indicate the main use of LCA as a decision support tool. TERI study also focuses on highlighting the use and importance of LCA for decision making in transport sector.

[11] TERI defined 'typical' projects as projects that do not have unusual features e.g. road and rail projects selected are in flat terrains, do not pass through forested areas, etc.

Conversion factors specifically embodied energy and CO_2 values of materials and fuels and tailpipe CO_2 emission factors of fuels are very critical for LCA analysis. India-specific values have primarily been used in this study to estimate energy and CO_2 impacts of material and fuel consumption. The study recognizes that technological and efficiency changes will take place in future which could reduce energy consumption and CO_2 in construction processes, materials production and transportation of materials. However, such efficiency improvements are not accounted while estimating the energy and CO_2 impacts for a 30 years period. It is assumed that the same level of efficiency will prevail for the 30 years period considered.

It should be noted that the LCA methodologies, approach and results for all countries will vary on account of several reasons like differences in construction technologies, use of materials, embodied energy and carbon factors, fuel emission factors, level of efficiency, etc. It is hence not appropriate to compare the LCA results derived for other countries with the Indian results derived in this study. TERI has hence not attempted to compare results with any international studies. Ideally, the results should be compared with LCA exercises for the same country; LCA methodology, system boundary should be same for the compared projects. Due to absence of any such study for India, TERI cannot compare the results derived in this study with any other study.

1.3.2 LCA scope/system boundaries and approach

1.3.2.1 Construction of the transport corridor/fixed infrastructure

Upstream impacts: Production of construction materials

Construction of any transport corridor requires consumption of materials. While on-site consumption of materials may not have any emissions, the production of most construction materials is an energy intensive process that also leads to CO_2 emissions. The LCA framework for this study includes this indirect energy consumption component related to material production, commonly referred as the 'embodied energy' of materials, and the resultant 'embodied CO_2' of materials. Steps followed to estimate embodied energy and CO_2 of materials include:

1. Estimating the quantity of materials consumed per kilometre (km) construction from the primary data collected for the selected transport projects (table 1.1).
2. Applying India-specific embodied energy and CO_2 coefficients for materials to estimate total embodied energy and CO_2 of materials consumed per km.[12] In case, India-specific embodied energy and CO_2 coefficients were not available, the same were derived from international literature.[13]

It should be noted that in case of BRTS and Metro rail, construction of stations[14] was also considered. Materials consumed for station construction were used to estimate the embodied energy and CO_2 of a station by following the steps 1and 2, discussed above.

[12] Source: AEI (2009)
[13] Source: Hammond and Jones (2008)
[14] One typical bus stop of Ahmedabad BRTS and One typical elevated metro station of Delhi Metro

Table 1.1 Selected transport projects for which construction data was collected*

National Highway	Four laning of Rohtak-Bawal National Highway, Haryana (NH-71)
Long-distance rail	Construction of Rewari-Rohtak new rail line, Haryana (single line)
Metro rail	Construction of Delhi Metro (elevated track and elevated station)
BRTS	Construction of Ahmedabad BRTS (BRTS corridor and one station)
City road	Construction of road in Delhi

* Note: It should be noted that the projects studied are typical projects and do not have unusual features. Road and rail projects selected are in flat terrains, do not pass through forested areas, etc. We have tried to select projects that are closest to being typical projects.

Upstream impacts: Transportation of construction materials

Once, the materials are produced in the manufacturing units, these are transported to the construction sites by motorized modes like trucks. There are two types of energy consumptions during this life stage – direct energy consumption by trucks and embodied energy of trucks. While the direct energy consumption component is included in the LCA framework, the indirect energy consumption i.e. embodied energy of trucks is not included because trucks used for transporting construction materials are capital assets that are re-used for several other construction projects and non-construction activities. The embodied energy impact of trucks used to transport materials would have to be distributed across all such construction projects and non-construction activities that a specific truck may serve throughout its life; the apportioned component may be insignificant. Also, this approach of excluding capital assets that are common to several projects is consistent with the ISO 14042 approach.

The embodied energy, embodied CO_2 and tailpipe CO_2 of direct energy consumption (diesel consumed) by trucks transporting materials to the site is included in the LCA framework. Steps followed to estimate the energy and CO_2 impact from transportation of materials are:

1. Estimating the total fuel consumed due to transportation of materials required for per km construction. Following data was collected for the selected projects (refer table 1.1) to estimate this fuel consumption:

    a. Quantities of materials transported and average leads for all materials

    b. Mode of transportation (truck, dumper, tractor, transit mixer, rail, etc.) and its fuel efficiency

    c. Average loading (per vehicle) and number of trips to transport materials

    For each material, fuel consumption was estimated based on mode used, number of trips, and average lead.

2. For the fuel consumption estimated in step 1, embodied energy and CO_2 were estimated by applying India-specific embodied energy and CO_2 coefficients.[15]

3. Tail-pipe CO_2 was estimated by using India-specific CO_2 emission factors[16].

[15] In case, India-specific embodied energy and CO_2 coefficients were not available, the same were derived from international literature; Source: Edwards et al (2006)

Table 1.2 summarizes the scope of LCA for the construction stage of transport projects.

It should be noted that in the construction stage, whatever, asset existed prior to construction is not included in the LCA. For e.g. in case of 4-laning of a NH, if a 2-lane road existed earlier, its construction is not accounted. Whatever, new construction that happens now for 4-laning of the NH is considered. It may include complete new construction of 2 lanes, improvement/strengthening of existing two-lanes, etc. Whatever, construction activity is undertaken to make a four-lane highway (on the existing 2-lanes) is considered.

Table 1.2 Upstream impacts during construction stage: Scope of LCA framework

Components of LCA	Included	Remarks
Production of construction materials		
Embodied energy and CO_2 of construction materials	√	India-specific coefficients - AEI (2009) International coefficient values - Hammond and Jones (2008)
Indirect energy consumption and CO_2 - Energy consumed for constructing infrastructure/ buildings, manufacturing machinery, etc. used for production of construction materials	X	*Rational for not including* ▪ Capital assets - common infrastructure used for producing construction materials for several projects; Embodied energy cannot be included in one project ▪ Difficult to apportion/distribute embodied energy to all projects – apportioned value may be very insignificant for one project ▪ Consistent with ISO 14042 approach – exclude capital assets that are common to several projects/systems ▪ None of the studied international applications, include these[17]
Transportation of construction materials		
Direct CO_2 due to fuel consumption by vehicles transporting construction materials	√	India-specific CO_2 emission factors - MoEF (2010) and ARAI (2007)
Embodied energy and CO_2 of fuel used	√	International coefficient values: TERI (2010); Edwards et al (2006)

[16] Source: MoEF (2010) and ARAI (2007)
[17] Birgisdóttir H (2005); Mroueh et al (2000); Mazri et al (2005); Treloar et al (2004); NTUA (2006)

Components of LCA	Included	Remarks
Apportioning the embodied energy of vehicles to per unit TKM transported	X	▪ Capital assets; common to several projects/non-construction activities ▪ Need to distribute impacts across all projects/activities – may be insignificant ▪ Consistent with ISO 14042 approach – exclude capital assets that are common to several projects/systems ▪ None of the studied international applications, include these

On-site impacts: On-site consumption of energy

On-site construction processes require energy to run construction machinery, generate heat, etc. Diesel, electricity and fuel oil are the most common fuels consumed on-site. On-site energy consumption for construction processes and CO_2 impact due to this is included in the LCA framework. Indirect energy consumption and CO_2 due to manufacturing of construction machinery and equipments, however, is not included in the LCA.

Steps followed to estimate the energy and CO_2 impact due to on-site energy consumption include:

1. Estimating the total energy consumed on-site (per km construction) for the selected projects (refer table 1.1). Following data was collected for the selected projects to estimate this energy consumption:
    a. Electricity consumption (from grid)
    b. Energy consumption for generators
    c. Consumption of petroleum products
    d. Types and number of machinery and equipments used on-site
2. For the energy consumption estimated in step 1, embodied energy and CO_2 were estimated by applying India-specific embodied energy and CO_2 coefficients.[18]
3. Tail-pipe CO_2 was estimated by using India-specific CO_2 emission factors.

On-site impacts: Removal of vegetation

Construction of transport corridors, many times, requires removal of vegetation, which leads to loss of the carbon sequestration potential of vegetation. The LCA framework includes the carbon sequestration (CS) potential lost due to on-site removal of vegetation for construction processes.

[18] In case, India-specific embodied energy and CO_2 coefficients were not available, the same were derived from international literature.

Vegetation removal for construction was found significant only in the case of National Highway project studied. However, the project contractors were undertaking compensatory afforestation to account for the loss of trees, which balances the CS potential lost. CS potential lost was hence not accounted. Only the CO_2 emissions due to end-use of vegetation removed in form of fuel wood was accounted. This was estimated by calculating the quantum of fuel wood from trees cut and then, applying CO_2 emission factor of fuel wood.

Table 1.3 summarizes the scope of LCA for the on-site impacts during construction stage of transport projects.

Table 1.3 On-site impacts during construction stage: Scope of LCA framework

Components of LCA	Included	Remarks
Direct CO_2 due to on-site fuel consumption (by construction machinery)	√	India-specific CO_2 emission factors: MoEF (2010) and ARAI (2007)
Embodied energy and CO_2 of fuel used (by construction machinery)	√	International coefficient values: TERI (2010); Edwards et al (2006)
Indirect energy consumption (energy consumed for manufacturing construction machinery/equipments used on site)	X	*Rational for not including* ▪ Number used is very large ▪ Machinery/equipments are common to several construction projects – need to proportionately distribute embodied energy to all projects where they are used – may not be significant per project ▪ Consistent with ISO 14042 approach – exclude capital assets that are common to several projects/systems ▪ None of the studied international applications, include these
Vegetation removal - CS potential lost	√	Didn't need to calculate due to compensatory vegetation being planted
Vegetation removal - use of some portion of removed trees as fuelwood	√	Estimating the quantum of fuel wood from trees cut and then, applying CO_2 emission factor of fuel wood

1.3.2.2 Operations on the transport corridor

Operations on transport corridors involve movement of the rolling stock. Energy consumption and CO_2 due to movement of rolling stock (direct) and manufacture of rolling stock (indirect) is included in the LCA. The scope however is limited to only one type of vehicle per mode i.e.

- Car in case of urban roads
- Bus in case of BRTS
- Metro rail (train) in case of MRTS
- Bus in case of National Highway
- Long-distance train (passenger) in case of long-distance rail transport

Table 1.4 describes the method adopted to estimate operational energy and CO_2 (direct) due to movement of rolling stock.

Table 1.4 Method adopted to estimate operational energy and CO_2 due to movement of rolling stock

Mode	Method	Data source
Long-distance train	Energy consumption for passenger services by Indian Railways was used to estimate energy and CO_2 per PKM	Annual Statistical Statements of Indian Railways (2010-11)
Long-distance bus	Energy consumption by long-distance buses of State Road Transport Undertakings (SRTUs) was used to estimate energy and CO_2 per PKM	Data published by Ministry of Road Transport and Highways (MoRTH) in 'Review of the Performance of State Road Transport Undertakings (2010-11)'
Metro rail (train)	Energy consumption by Delhi Metro was used to estimate energy and CO_2 per PKM	PDD (Project Design Document) submitted by DMRC to UNFCCC (to get carbon credits for Phase-2 of Delhi Metro)
BRTS	Energy consumption data for Ahmedabad BRTS was used to estimate energy and CO_2 per PKM	Data provided by CEPT, Ahmedabad
Car	Average fuel efficiency and occupancy of cars (petrol, diesel, CNG car) was used to estimate energy and CO_2 per PKM	Data collected from SIAM, BEE, and TERI publications

Detailed methods used for estimating operational energy and CO_2 due to movement of rolling stock are discussed in the subsequent chapters.

With regard to indirect energy consumption and CO_2 due to manufacture and maintenance of rolling stock, the original intent was to collect India- specific data from auto industries. However, this information was not readily forthcoming on account of commercial confidentiality. International literature was hence reviewed to understand the embodied energy and CO_2 values for rolling stock (on account of manufacturing and full-life maintenance). The most comprehensive analysis on the subject was found in Chester and Horvath (2009), Chester (2008), and Chester et al. (2010). Embodied energy and CO_2 values for rolling stock have been derived for USA in these papers.

Table 1.5 summarizes the scope of LCA for the operations stage of transport projects.

Table 1.5 Operations stage: Scope of LCA framework

Components of LCA	Included	Remarks
Direct energy consumption and CO_2 (tailpipe and embodied) emissions from vehicles moving on the transport corridor	√	Energy consumed per passenger km estimated using actual fuel consumption data[19] for different modes; India-specific CO_2 emission factors used
Indirect energy consumption and CO_2 i.e. energy consumed and CO_2 emitted due to manufacturing and maintenance of rolling stock	√	Data estimated for USA considered

1.3.2.3 Maintenance of the transport corridor

In case of maintenance[20], energy and CO_2 impacts due to following are included in LCA:

- Annual routine maintenance
- Periodic maintenance/ renewal

Annual routine maintenance

Annual routine maintenance data was collected for a few selected projects (table 1.6). Only material consumption for annual maintenance was considered to estimate the embodied energy and CO_2 due to the same.[21] Embodied energy and CO_2 due to energy consumption for on-site activities and transport of materials/labour was not considered. To estimate the impact of total annual maintenance activities for 30 years, it was assumed that the annual maintenance activity will remain the same for all years as for the year for which maintenance data is collected.

It is recognized that technological and efficiency changes will take place in future which could reduce energy consumption and CO_2 in construction processes, materials production and transportation of materials. However, such efficiency improvements are not accounted

[19] Except in case of car
[20] Only maintenance of corridors/tracks is estimated; maintenance of stations is not estimated
[21] Detailed steps to estimate embodied energy and CO_2 due to material consumption are discussed section 1.3.1.

while estimating the energy and CO_2 impacts due to maintenance activities in 30 years. It is assumed that the same level of efficiency will prevail for the 30 years period considered.

Table 1.6 Selected transport projects for which maintenance data was collected[22]

National Highway	Delhi-Agra National Highway
Long-distance rail	Delhi-Bathinda rail line
Metro rail	Delhi Metro
BRTS	Ahmedabad BRTS
City road	A typical road in Delhi

Periodic maintenance/renewal

Periodic maintenance data was collected for the projects listed in table 1.6. In case of road projects[23] (NH, BRT and urban road), periodic maintenance involves adding a renewal coat to the wearing course/surface. Renewal coat is periodically added at a predetermined frequency that is usually determined based on the expected traffic. Data on one periodic renewal (consumption of materials only) for the selected projects was collected and then used to estimate total periodic maintenance activities for a 30 year period, based on the no. of times the periodic renewal will take place during 30 years time. Data on frequency of periodic renewals was also collected from project contractors/implementing agencies.

In case of rail projects (long-distance and metro rail), the key periodic renewal activities in 30 years period were identified like replacement of sleepers, replacement of rails, through screening of ballast, etc. The energy and CO_2 impacts of these activities were then estimated following the same steps as discussed in the construction section. It should be noted that only material consumption is considered in periodic maintenance activities. Energy consumption for on-site activities and transport of materials/labour is not considered. As in the case of annual maintenance estimations, same level of efficiency of processes/ transportation as present is assumed for future. Table 1.7 summarizes the scope of LCA for the maintenance stage of transport projects.

Table 1.7 Maintenance stage: Scope of LCA framework

Components of LCA	Included	Remarks
Activities associated with annual and periodic maintenance works:		Only material consumption considered in maintenance activities. Energy efficiency levels in future assumed to remain same as today.
▪ **Material consumption (embodied energy and CO_2)**	√	
▪ **Energy use (direct impact and embodied energy)**	X	

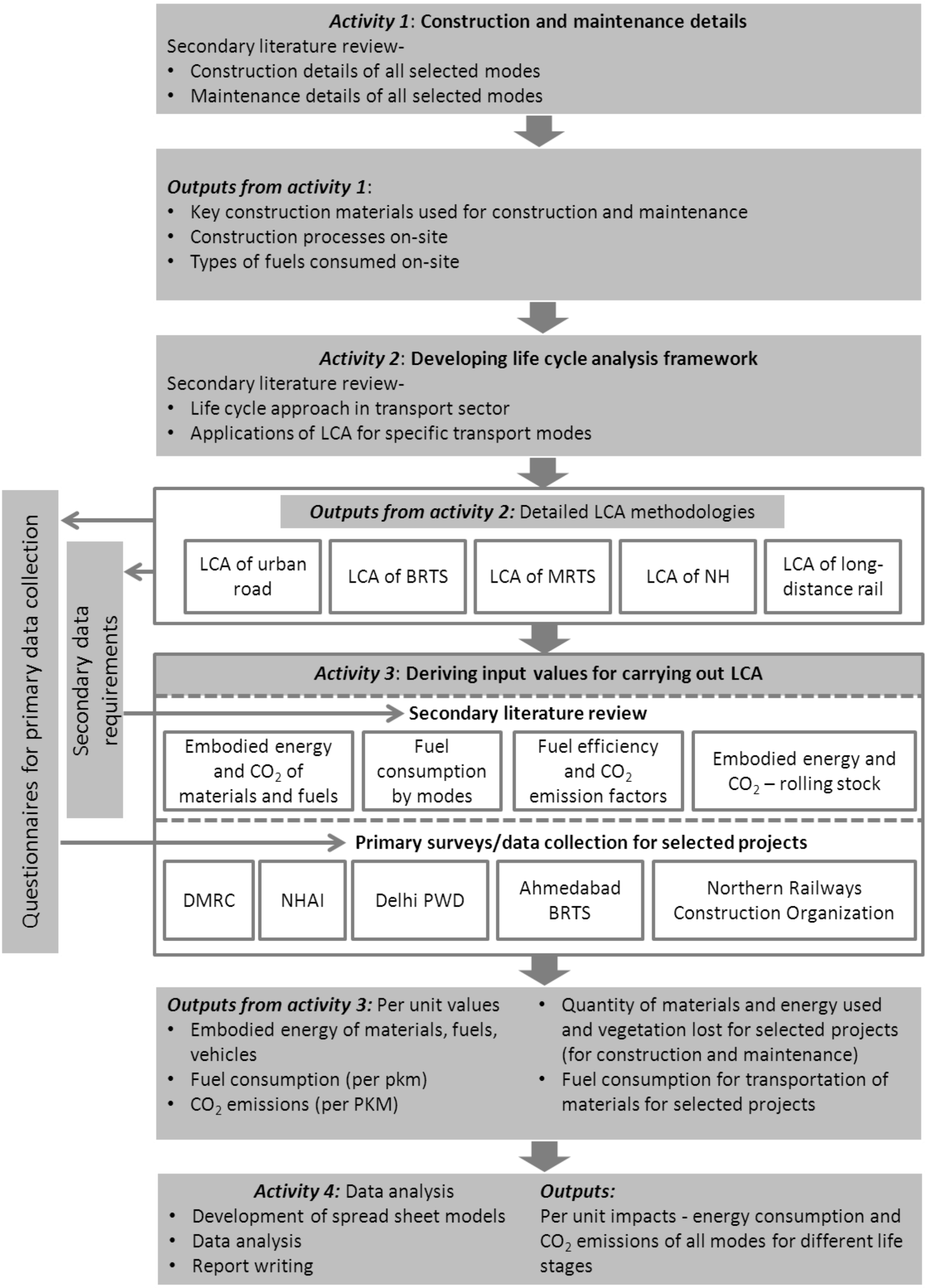
[22] Note: It should be noted that the projects studied are typical projects and do not have unusual features. Road and rail projects selected are in flat terrains, do not pass though forested areas, etc. We have tried to select projects that are closest to being typical projects.

[23] Bituminous roads

1.3.3 Key activities in the study

Based on LCA scope/approach defined in the previous sections, detailed activities were drawn up for the study (figure 1.1). The proposed activities were carried out to meet the objectives of this study.

Figure 1.1 Key activities in the study



1.4 Report structure

Volume I – LCA framework and findings

- Chapter 1 of the report gives the background and the objectives of the study. The scope of LCA and the approach adopted to carry out LCA for selected modes of transport is described.
- Chapter 2 describes the conceptual framework of LCA model developed by TERI to estimate the life cycle energy and CO_2 impacts of the selected modes of transport.
- Chapters 3 to 7 give the results of life cycle analysis of all selected modes of transport. Impacts of construction, maintenance and operations phases of transport modes are discussed and then summarized to reflect the total impacts for a time period of 30 years.
- Chapter 8 of the report gives the conclusions for the study.

Volume II – Summary of literature reviews and primary questionnaires used for data collection

Detailed review of codes, design standards, manuals, etc. was carried out to understand construction practices for transport infrastructure. The review was used to identify materials and energy inputs for construction processes. Detailed questionnaires were developed based on this review to collect primary data on construction and maintenance of transport infrastructure. Additionally, literature review was carried out to understand and choose life cycle energy and CO_2 impact values of rolling stock.

Volume II summarizes the above mentioned reviews of codes, design standards, manuals, and secondary literature. Volume II also gives the questionnaires that were used to collect primary data for the transport projects selected in the study.

Chapter 2: Quantitative estimation of life cycle impacts: Spread sheet model

TERI has developed a spread sheet model to carry out the quantitative analysis related to life cycle analysis. Table 2.1 gives the framework of the spread sheet model developed.

Table 2.1 Framework of spread sheet model developed for LCA

Colours indicate the following:

	Input values
	Output values

(1) Construction phase - Embodied energy and CO_2 of materials used								
Construction materials used	Unit	Quantity used per km	Embodied energy coefficient (EE)	Unit (EE)	Total EE (MJ)	CO_2 coefficient	Unit (CO_2 coefficient)	Total CO_2 (kg)
Aggregate								
Sand								
Steel								
Cement								
Cut								
Bitumen								
Mix material								
Bitumen emulsion								
Cut/Fill								
Paint								
Rubber								
Cast iron								
Cement concrete								
Bricks								
Total								
(2) Fuels being burnt/used on construction site								
Fuel used	Unit	Quantity used per km	Embodied energy coefficient (EE)	Unit (EE)	Total EE (MJ)	CO_2 coefficient	Unit (CO_2 coefficient)	Total CO_2 (kg)
Diesel								
Electricity								
LPG								
LDO								
Kerosene								
Petrol								
Total								

(3) Fuel consumption for transport of materials and labour/staff								
Fuel used	Unit	Quantity used per km	Embodied energy coefficient (EE)	Unit (EE)	Total EE (MJ)	CO_2 coefficient	Unit (CO_2 coefficient)	Total CO_2 (kg)
Diesel								
Petrol								
Total								
(4) Removal of vegetation								
Fuel wood	Unit	Quantity attributed per km	Embodied energy coefficient (EE)	Unit (EE)	Total EE (MJ)	CO_2 coefficient	Unit (CO_2 coefficient)	Total CO_2 (kg)
Fuel wood used from the cut trees								
Total								
(5) Construction of 1 station (Only embodied energy of key materials used considered)								
Construction materials used	Unit	Quantity used per km	Embodied energy coefficient (EE)	Unit (EE)	Total EE (MJ)	CO_2 coefficient	Unit (CO_2 coefficient)	Total CO_2 (kg)
Concrete								
Steel reinforcement								
Structural steel								
Galvanized steel								
Steel fabrications								
Bricks								
Kota stone								
PVC								
Ceramic								
Aluminium								
Total								
Grand Total								

Chapter 3: LCA results - National Highway

3.1 Construction

In order to estimate the embodied energy and CO_2 per kilometre (km) construction of a National Highway (NH), an on-going NH construction project was studied. The details of the construction project are given in the next section.

3.1.1 Project studied

Four laning of Rohtak-Bawal (Haryana) section of NH-71 was studied. The details about the project are given in table 3.1. Rewari Project Implementation Unit (PIU) of National Highways Authority of India (NHAI) facilitated the data collection from Kurukshetra Expressway Pvt. Ltd. (KEPL). KEPL is executing the project on Design, Build, Finance, Operate and Transfer (DBFOT) basis.

Table 3.1 Details of the NH construction project studied

Project:	**Four Laning of Rohtak-Bawal section of NH-71 under NHDP III on DBFOT basis**		
State:	Haryana		
Road start and end points:	From- Chainage 363.30	To- Chainage 445.85	Total distance between the two points: 82.55 km (4 lanes)
Road length constructed as on date when construction data was collected:	10.37 km		
Construction duration:	Start date- 10th May, 2011 Expected end date- November, 2013		
Design life of pavement (years):	10 Years		
Cross-section details	60 m ROW, 4 lane road, 8.75 m one-side carriage way, 4.5 m median, 1.5 meter shoulder, 8.0 m width service road one-side (In urban stretches and by-passes i.e. 16 km length - service road is on both sides)		

Source: Data provided by KEPL

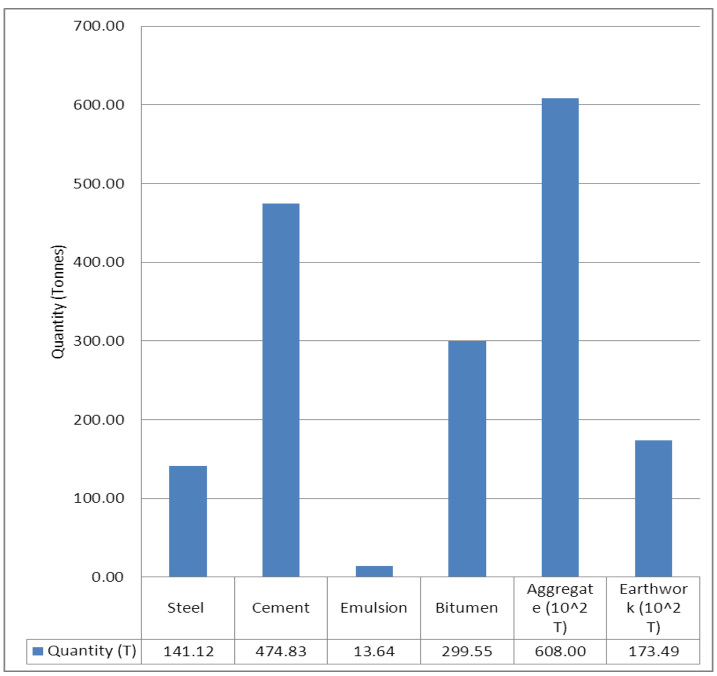
3.1.2 Consumption of materials during construction

Key materials consumed for NH construction include:

- Aggregate
- Bitumen
- Bitumen emulsion
- Cement
- Steel
- Earth (cut and fill)

Per kilometre consumption of key materials in construction of NH is given in figure 3.1.

Figure 3.1 Consumption of key materials- 1 km NH construction



Source: Primary data collected by TERI from KEPL for Rohtak-Bawal NH construction

Construction of 1 km NH involves significant consumption of aggregates (coarse/fine); about 60 thousand tonnes of aggregates are consumed per km. Construction also involves substantial amount of earthwork in the form of cut and fills on the site. In the Rohtak-Bawal section studied, earthwork to the tune of about 17 thousand tonnes was carried out. About 300 tonnes of bitumen was used per km. The road section studied also involved use of cement (about 475 tonnes), and steel[24] (about 140 tonnes), primarily for construction of culverts, small bridges, kerb channels, etc.

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[24] Steel reinforcement and structural steel

Photo 3.1 Photographs of construction of Rohtak-Bawal NH

Embodied energy and CO_2 due to material consumption

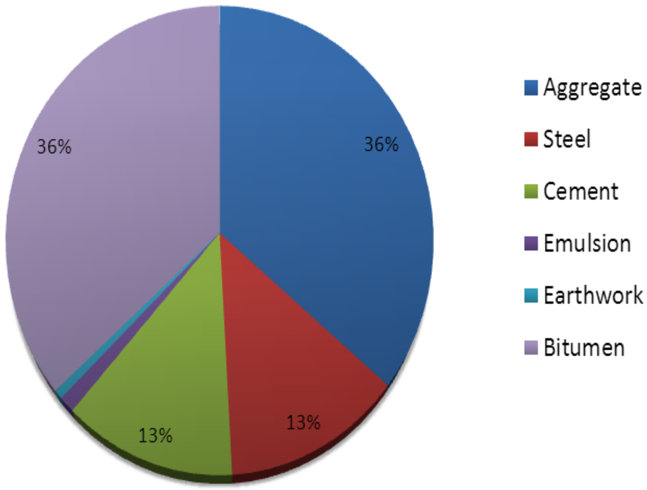
As stated in the previous chapters, the production of materials requires use of energy and leads to CO_2 emissions. This is referred as embodied energy or embodied CO_2 of materials. To estimate the embodied energy and CO_2 of materials used in construction of NH, India-specific embodied energy and CO_2 coefficients for materials were used.[25] The embodied energy and CO_2 of materials used per km NH construction is estimated to be about **37 TJ and 2,300 tonnes**, respectively. Aggregates and bitumen have maximum contribution (36% each) to the embodied energy of per km materials used (figure 3.2). While the quantity of bitumen used per km (300 tonnes) is much less than aggregates used per km (60,000 tonnes), it still has significant contribution to per km embodied energy of NH, as its per unit embodied energy is very high as compared to that of aggregates.[26] Use of steel and cement contributes about 25% embodied energy. In case of embodied CO_2 per km materials used, aggregates have the maximum contribution of about 56%, followed by steel (19%), cement (18%) and bitumen[27] (6%) (figure 3.3).

[25] In case, India specific embodied energy coefficients were not available for some materials, the same were derived from international literature.

[26] Embodied energy - Bitumen: 44.70 MJ/kg, Coarse aggregate: 0.22 MJ/kg, Fine aggregate (sand): 0.02 MJ/kg

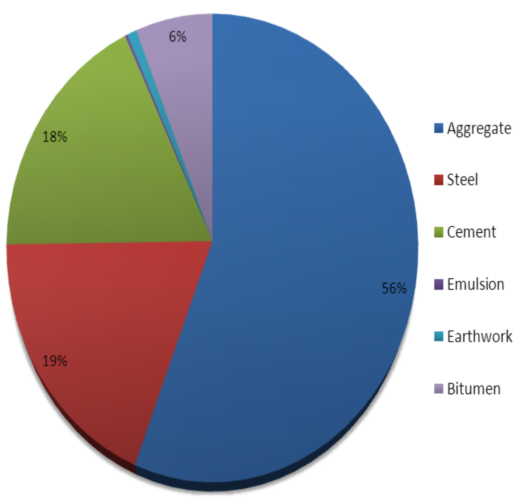
[27] Bitumen has high contribution in embodied energy (36%), but not in embodied CO_2 (6%). This is because bitumen has a very high embodied energy coefficient (44.7 MJ/kg). Embodied CO_2 coefficient of bitumen is 0.48 kg CO_2/kg bitumen.

Figure 3.2 Contribution of different materials to embodied energy of materials used per km NH construction



Source: Analysis by TERI

Figure 3.3 Contribution of different materials to embodied CO_2 of materials used per km NH construction



Source: Analysis by TERI

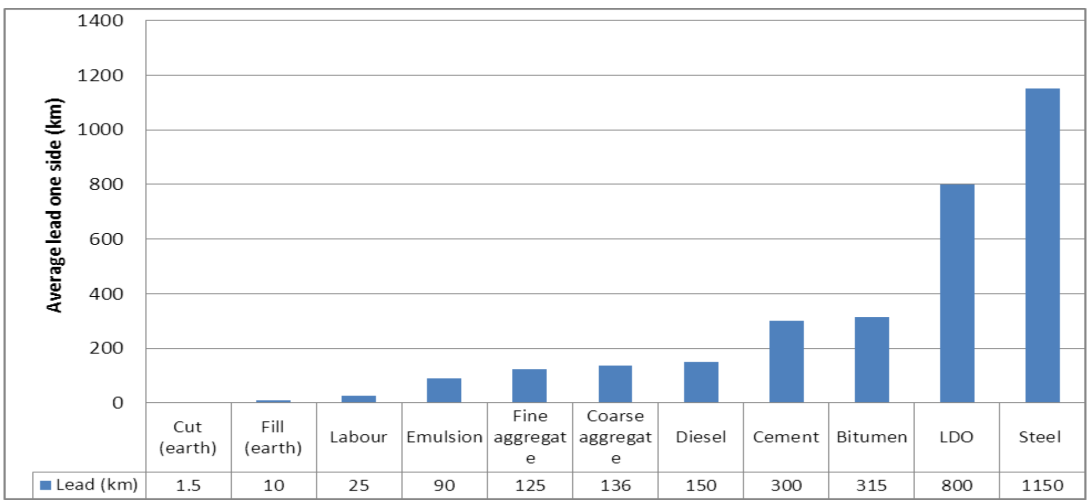
3.1.3 Energy consumption during construction - Transportation of materials and labour and on-site energy consumption

Transportation of materials and labour to and from construction site also leads to energy and CO_2 impacts due to direct energy consumption for transportation.[28] The amount of energy used for transportation of materials/labour depends on three key factors:

- Distance (lead) travelled
- Quantity transported
- Mode used for transportation

All these factors were considered to estimate the energy used to transport materials/labour to and from the site. For the Rohtak-Bawal NH construction, the average lead of materials and labour transportation ranged from 1.5 km to 1,150 km (figure 3.4). Road-based modes like tippers, dumpers, trucks, tankers, bulkers, etc., all of which consume diesel, were used for transportation. The number of trips for transportation were estimated based on quantities transported (figure 3.1) and average loading[29] on different modes and then used to estimate the diesel consumption.[30]

Figure 3.4 Average lead for materials and labour transportation



Source: Primary data collected by TERI from KEPL for Rohtak-Bawal NH construction

In addition to energy consumption for transportation of materials, energy is also needed to carry out on-site construction works that involve running of machinery, equipments and vehicles. On-site energy consumption was also considered in the study. For the Rohtak-Bawal NH, the key fuels consumed on-site included diesel, Light Diesel Oil (LDO) and LPG.

[28] As stated in the previous chapters, only the energy and CO_2 impacts of direct energy consumption for transportation are considered. Embodied energy and CO_2 of vehicles transporting materials/labour is not considered.

[29] Average loading data was taken from project contractors (KEPL).

[30] To and fro trips of vehicles have been considered while calculating fuel consumption i.e. if a truck is making a trip to transport cement to the site, diesel consumption has been estimated for it's to and fro trip (trip from cement factory to site and back to factory).

Embodied energy and CO_2 due to energy consumption during construction

India-specific embodied energy coefficients[31] and CO_2 emission factors[32] for fuels like diesel, LDO, and LPG were used.[33] The total embodied energy and CO_2 due to energy consumption for transportation of materials and labour and on-site energy needs (for construction of 1 km NH) are estimated to be about **2.32 TJ and 1,100 tonnes** respectively.

3.1.4 Removal of vegetation

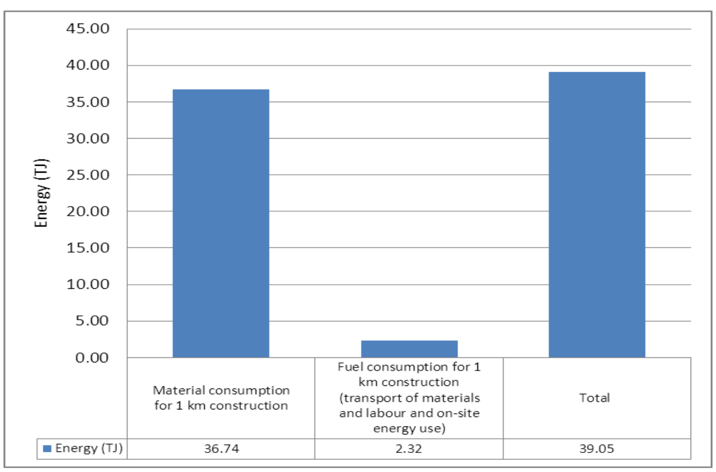
A total of about 7,000 trees were cut for the entire length of 82.55 km of Rohtak-Bawal section. The predominant species of trees cut were *Kikar, Sheesham,* and *Neem.* As stated earlier, clearance of vegetation can lead to a certain amount of carbon sequestration potential being lost. However, since in this case, the road contractors were required to plant equal number of new trees in order to compensate the tree loss, it makes up for the carbon sequestration potential lost on account of trees cut during construction. The CO_2 sequestration potential lost due to removal of vegetation is therefore not accounted.

Some portions of trees removed are typically put to use as fuel wood, which contributes to direct CO_2 emissions. The CO_2 emissions on account of wood burning were estimated; **5 tonnes** of CO_2 can be attributed to per km road construction in case of Rohtak-Bawal section to account for use of vegetation removed during construction as fuelwood.

3.1.5 Summary construction phase - Embodied energy and CO_2

The embodied energy and CO_2 emissions estimated for construction of 1 km NH are summarized in figures 3.5 and 3.6. Total embodied energy and CO_2 in constructing 1 km NH are estimated at about **39 TJ and 3,450 tonnes**, respectively.

Figure 3.5 National Highway - Embodied energy (TJ) per km construction



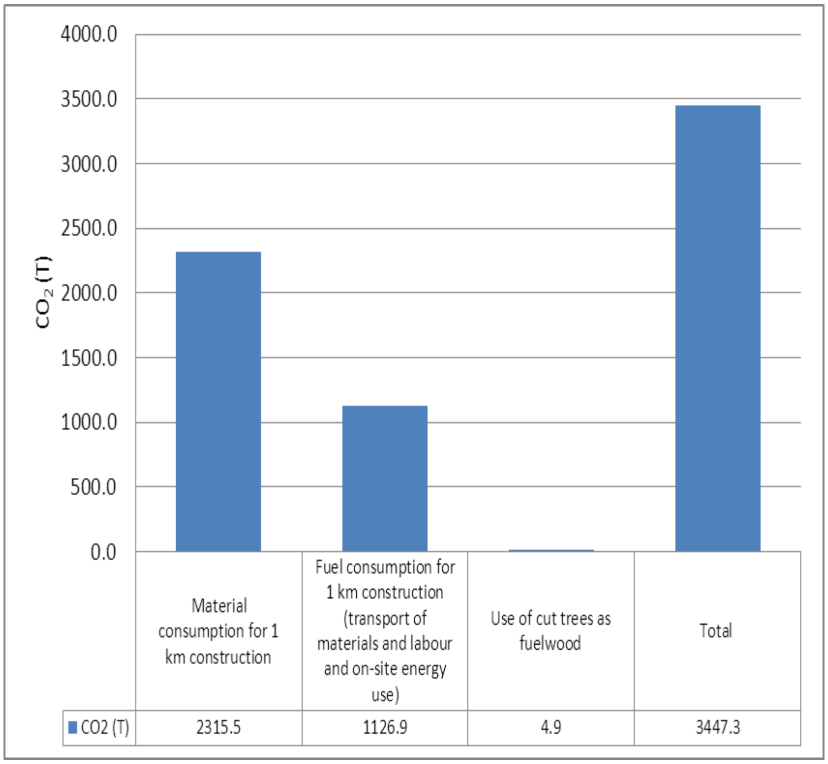
Source: Analysis by TERI

[31] Energy required to produce 1 unit of fuel.

[32] CO_2 emission factors used for fuels include embodied CO_2 in fuels i.e. CO_2 emitted to produce 1 unit of fuel and CO_2 at tail-pipe due to combustion of fuel.

[33] In case, India specific embodied energy coefficients were not available, the same were derived from international literature.

Figure 3.6 National Highway - Embodied CO_2 (tonnes) per km construction



Source: Analysis by TERI

3.2 Maintenance

Maintenance of NH-2- Delhi-Agra section was studied in order to estimate the embodied energy and CO_2 per kilometre (km) maintenance of a National Highway. The details of Delhi-Agra NH section are given in the next section.

3.2.1 Project studied

Maintenance of NH-2- Delhi-Agra section was studied. The details about the project are given in table 3.2. Data for maintenance of 123.65 km long bituminous road between Delhi and Agra was collected.[34] Faridabad Project Implementation Unit (PIU) of NHAI facilitated the data collection from Aretefact Projects Ltd. (APL), Faridabad, the consultants for Delhi-Agra maintenance project.

[34] Total length of NH between Delhi-Agra is 179.10 km, of which 123.65 km is bituminous road and 55.35 km is cement concrete road. Data was collected only for the bituminous road.

Table 3.2 Details of the NH maintenance project studied

Project:	**Delhi-Agra (NH-2) maintenance** **(Maintenance of bituminous road)**		
State:	Haryana and Uttar Pradesh		
Road start and end points:	From- km 20.5	To- km 199.6	Total distance between the two points: 179.1 km
Road length for which maintenance data was collected:	123.65 km bituminous road		
Road construction year:	1995-96		
Periodic maintenance cycle:	Bituminous overlays after every 5 years		
Cross-section details	**Four Lane road** Carriage way width one side - 8.5 m Median - 5-7 m Shoulder - 1 m (unpaved) & 1.5 m (paved) Service road - 5.5 m (one side)		

Source: Data provided by Aretefact Projects Ltd. (APL)

3.2.2 Annual routine maintenance

Key annual routine maintenance works involve the following:

- Patch work,
- Crack sealing,
- Painting,
- Repairing of road furniture,
- Median fencing, etc.

Data provided by Aretefact Projects Ltd. on maintenance of Delhi-Agra NH was used to estimate per km material consumption[35] for annual routine maintenance activities. Table 3.3 gives the quantities consumed for Delhi-Agra section.

[35] As stated in Chapter 1, only material consumption is considered while estimating the embodied energy and CO_2 due to maintenance activities (annual and periodic).

Table 3.3 Annual routine maintenance of NH - Material consumption per km

Materials	Consumption (in tonnes) per km maintenance (annual)
Aggregate	23.5
Cement	0.2
Sand	14.1
Bitumen	1.2
Mix material	24.7
Fill (earth)	7.2

Source: Primary data collected by TERI from APL for Delhi-Agra NH annual maintenance

The above consumption translates into **0.19 TJ embodied energy and 8.3 tonnes embodied CO_2**

3.2.3 Periodic maintenance (30 years duration)

Periodic maintenance in case of bituminous roads involves adding a renewal coat to the wearing course/surface. Renewal coat is added at a predetermined frequency that is usually determined based on the expected traffic. In the case of Delhi-Agra NH studied, the periodic renewal/maintenance was being carried out at an interval of 5 years. Material consumption for periodic maintenance was estimated based on data for Delhi-Agra NH section provided by APL; table 3.4 gives the per km material consumption for one periodic renewal for the section.[36]

Table 3.4 Periodic renewal (once in 5 years) of NH (bituminous surface) - Material consumption per km

Materials	Consumption (in tonnes) per km periodic maintenance (5-yearly)
Aggregate	668.61
Sand	74.29
Bitumen	39.10
Mix material	742.90

Source: Primary data collected by TERI from APL for Delhi-Agra NH maintenance

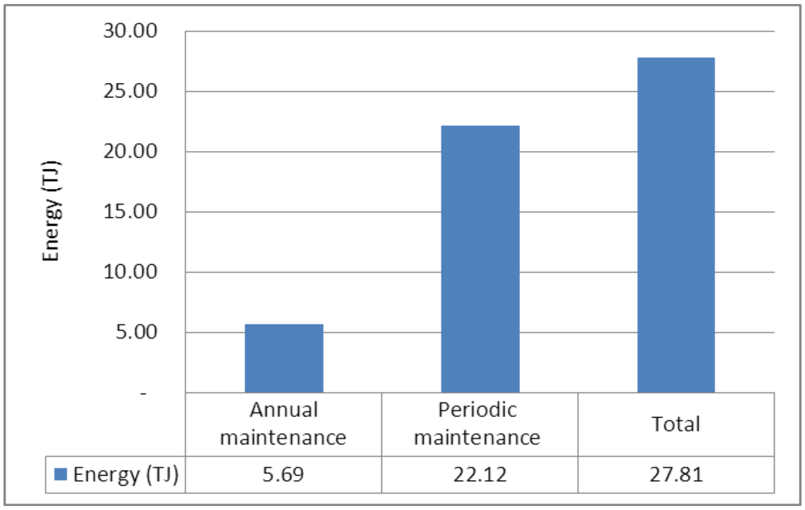
[36] It should be noted that the maintenance activities considered do not include the consumption of materials for strengthening of the road.

Consumption of materials for periodic renewal in 30 years period translates into **22.1 TJ embodied energy and 824 tonnes embodied CO_2**.

3.2.4 Summary maintenance phase - Embodied energy and CO_2

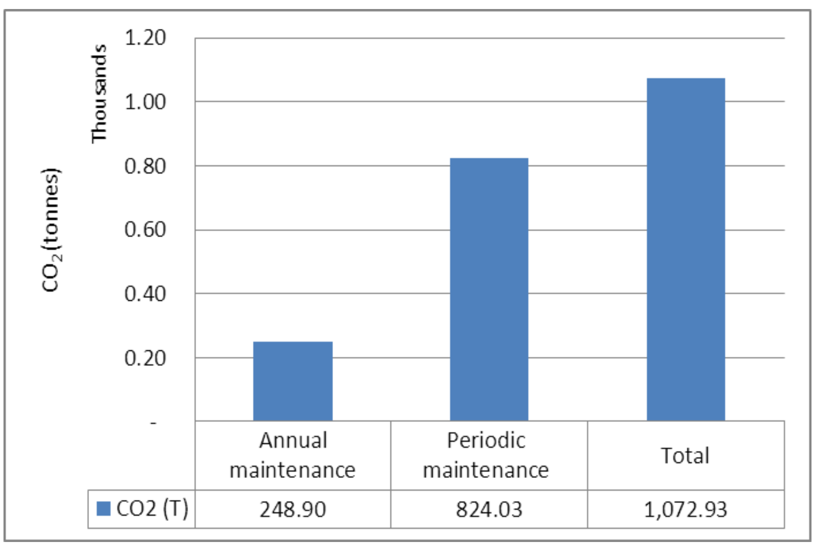
Annual routine maintenance and periodic maintenance/renewal for a 30 year period translates into **embodied energy of about 28 TJ and embodied CO_2 of about 1,070 tonnes** (figures 3.7 and 3.8).

Figure 3.7 Maintenance of NH for 30 years - Embodied energy (TJ) per km



Source: Analysis by TERI

Figure 3.8 Maintenance of NH for 30 years - Embodied CO_2 (tonnes) per km



Source: Analysis by TERI

3.3 Operations

Operational energy consumption of long-distance passenger buses was estimated by using data on physical performance of State Road Transport Undertakings (SRTUs).[37] Following data was used to estimate energy consumption per passenger km (PKM) and CO_2 per PKM for long-distance bus operations.

- Average kms per bus per day
- Average fuel efficiency per bus
- Average number of passengers carried per bus per day
- Average lead of passengers[38]

The above data was compiled for 16 SRTUs. Table 3.5 shows the energy consumption per PKM and CO_2 per PKM derived for the 16 SRTUs. **Average energy consumption and CO_2 of the 16 SRTUs is estimated to be around 221.9 kJ/PKM and 17.9 g/PKM**, respectively.

Table 3.5 Operational energy consumption per PKM and CO_2 per PKM of SRTUs (2010-11)

SRTU	Diesel consumption	CO_2[39]
	kJ/PKM	g/PKM
Andhra Pradesh SRTC	212.8	17.1
Bihar SRTC	284.3	22.9
Gujarat SRTC	194.7	15.7
Haryana ST	218.1	17.6
Karnataka SRTC	201.5	16.2
Maharashtra SRTC	261.3	21.0
North Bengal STC	253.3	20.4
Northern Eastern Karnataka RTC	219.9	17.7

[37] Data published by Ministry of Road Transport and Highways (MoRTH) in '**Review of the Performance of State Road Transport Undertakings (2010-11)**' was referred.
[38] Derived by dividing total annual PKM by total annual passengers carried
[39] Embodied CO_2 of diesel included.

SRTU	Diesel consumption	CO_2[39]
	kJ/PKM	g/PKM
North Western Karnataka RTC	210.5	16.9
Orissa SRTC	247.8	19.9
Rajasthan SRTC	197.7	15.9
South Bengal STC	231.6	18.6
State Exp. TC TN Ltd	223.4	18.0
Uttar Pradesh SRTC	211.6	17.0
Chandigarh TU	196.7	15.8
Delhi TC (long distance buses)	184.7	14.9
Average	**221.9**	**17.9**

Source: Analysis by TERI

3.4 Embodied energy of rolling stock

As described in the LCA framework, rolling stock like buses, trains, cars, etc. used during operations phase of transport modes for movement of people/goods also have embodied energy and CO_2 on account of manufacturing and maintenance processes[40]. While it was attempted to estimate India-specific energy and CO_2 values for rolling stock, the same could not be accomplished on account of commercial confidentiality of such data. International literature was hence reviewed to understand embodied energy and CO_2 values for rolling stock. The most comprehensive analysis on the subject was found in Chester and Horvath (2009a and 2009b), Chester (2008), and Chester et al. (2010). Embodied energy and CO_2 values for rolling stock have been derived for USA in these papers; table 3.6 gives the values for buses in USA.

[40] End-of-life embodied energy and CO_2 of rolling stock are not considered as dismantling/recycling vehicles are not widely adopted practices in Indian context.

Table 3.6 Embodied energy and CO_2 values (vehicle manufacture and maintenance) for rolling stock - Bus

Buses	Energy (TJ)		CO_2 (T)	
	Vehicle manufacture	Vehicle maintenance (full life)	Vehicle manufacture	Vehicle maintenance (full life)
Diesel bus (1)	2.0	0.3	160.0	22.0
Diesel bus (2)	1.7	0.3	140.0	22.0

Source: Chester and Horvath (2009b)

3.5 Summary - National Highway

Table 3.7 Life cycle embodied energy and CO_2 - NH

NH	Phase	Embodied energy	Unit	Embodied CO_2	Unit	Remarks
Fixed infrastructure	Construction	39.1	TJ/km	3,442.4	T/km	India-specific values, Based on TERI's analysis
	Maintenance (30years)	27.8	TJ/km	1,072.9	T/km	
Rolling stock	Manufacture	1.7	TJ/bus*	140.0	T/bus*	USA-specific values, Source: Chester and Horvath (2009b)
	Maintenance (full life)	0.3	TJ/bus*	22.0	T/bus*	
	Operations (long-distance bus; diesel)	221.9	kJ/PKM	17.9	g/PKM	India-specific values, Based on TERI's analysis

*Diesel bus

Chapter 4: LCA results - Long-distance rail

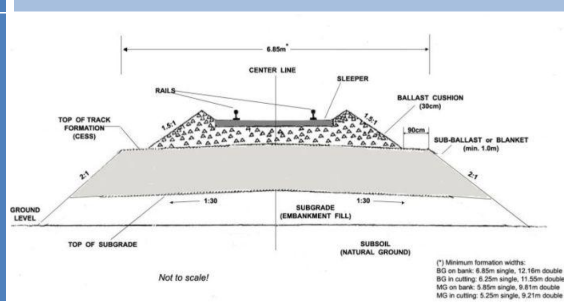
4.1 Construction

A recently completed rail track construction project was studied in order to estimate the embodied energy and CO_2 per kilometre (km) construction of rail track. The details of the construction project are given in the next section.

4.1.1 Project studied

Construction of the new rail line between Rewari and Rohtak was studied. The details about the project are given in table 4.1. The line constructed between Rewari and Rohtak is a single line with a length of about 75 km.[41] Data regarding construction details of the project was provided by the Northern Railways Construction Organization (NRCO).

Table 4.1 Details of the rail track construction project studied

Project:	**Construction of new rail line between Rewari and Rohtak**		
State:	Haryana		
Rail start and end points:	From- Rewari	To- Rohtak	Total distance between the two points: 75 km
Rail length constructed as on date when construction data was collected:	75 km main line and 7 km loop line		
Construction duration:	Start date- October, 2007 End date- March, 2011		
Design life of new line(years):	Depends on traffic (Different components of the track have different design life)		
Cross-section details			

Source: Data provided by NRCO

[41] Main line length - 75 km (single line); Loop line - 7 km

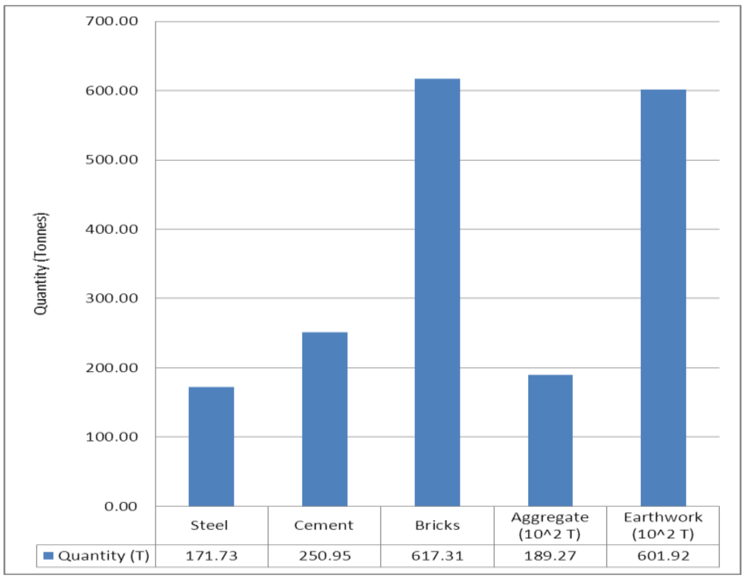
4.1.2 Consumption of materials during construction

Key materials consumed for rail track construction include:

- Aggregate
- Steel
- Cement
- Bricks[42]
- Earth (cut and fill)

Per kilometre consumption of key materials in construction of rail track is given in figure 4.1.

Figure 4.1 Consumption of key materials- 1 km rail track construction



Source: Primary data collected by TERI from NRCO for Rewari-Rohtak rail line construction

Earthwork is an important activity during rail track construction. Construction of 1 km rail track length in case of Rewari-Rohtak line involved earthwork to the tune of about 60 thousand tonnes. There is also a significant consumption of aggregates (coarse/fine); about 19 thousand tonnes of aggregates were consumed per km track construction in case of Rewari-Rohtak line. The other key materials consumed include steel (for rails, track fittings and fastenings and reinforcement) and cement (for sleepers, bridges and foundations for signals). In case of Rewari-Rohtak line, about 170 tonnes of steel and 250 tonnes of cement were used per km. Additionally, bricks were also used (610 tonnes/km) for bridges, signalling work, etc.

It should be noted that the material consumption discussed above includes material consumption for key signalling works on the track, e.g. earthwork, use of reinforced concrete and bricks for foundation for signal posts and laying of cables[43], etc. Key materials used in signal posts are also included.

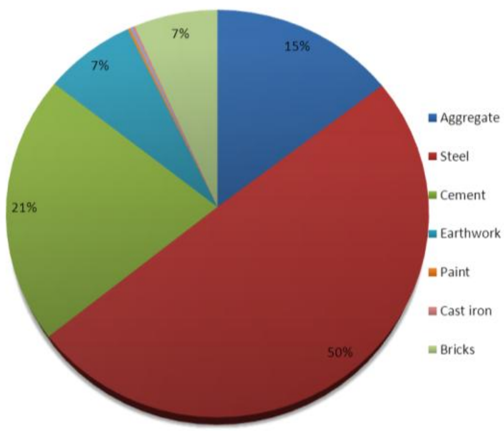
[42] Used in bridges, signalling works

[43] Note: Materials used in cables (copper and rubber) are not included due to lack of data.

Embodied energy and CO_2 due to material consumption

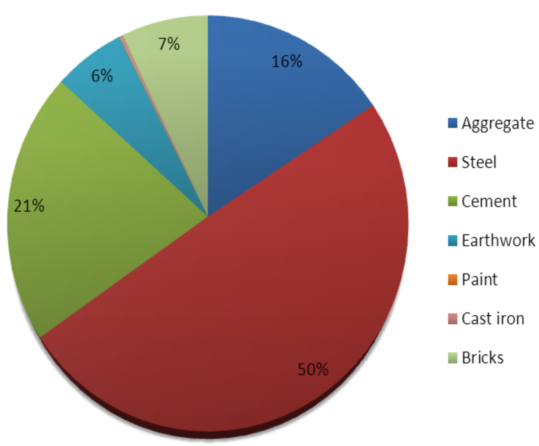
India-specific embodied energy and CO_2 coefficients for materials were used to estimate embodied energy and embodied CO_2 of materials consumed during construction.[44] The embodied energy and CO_2 of materials used per km rail track construction in the Rewari-Rohtak line is estimated to be about **11.5 TJ and 1,000 tonnes**, respectively. Steel and Cement are responsible for about 70% embodied energy, followed by aggregates, which account for about 15% of the embodied energy (figure 4.2). In case of embodied CO_2 also, steel and cement together have maximum contribution (about 70%), followed by aggregates (16%) (figure 4.3).

Figure 4.2 Contribution of different materials to embodied energy of materials used per km rail track construction



Source: Analysis by TERI

Figure 4.3 Contribution of different materials to embodied CO_2 of materials used per km rail construction



Source: Analysis by TERI

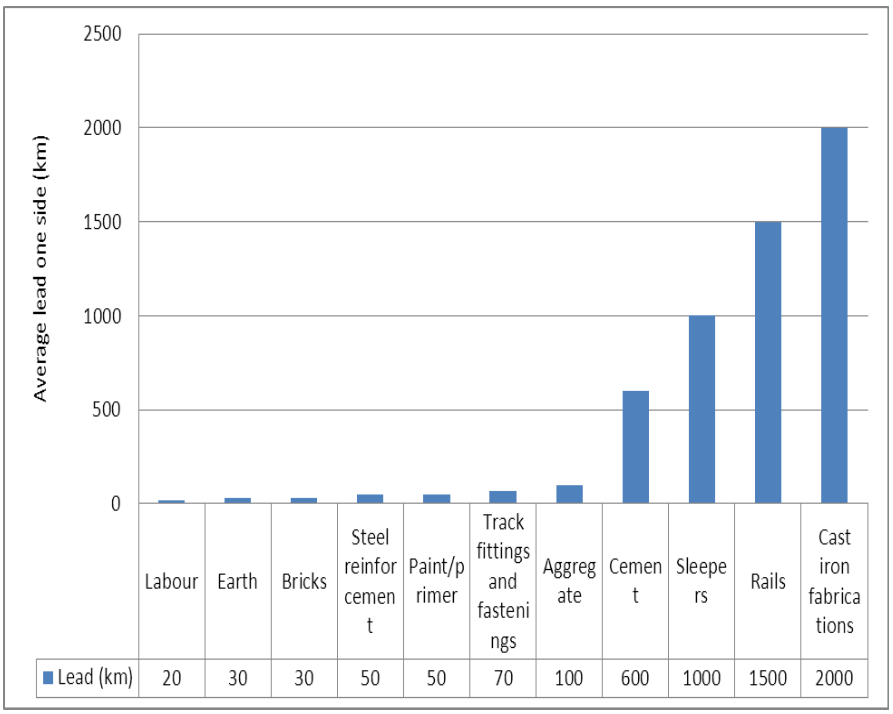
[44] In case, India specific embodied energy coefficients were not available for some materials, the same were derived from international literature.

4.1.3 Energy consumption during construction - Transportation of materials and labour and on-site energy consumption

As stated previously, transportation of materials and labour to and from construction site also leads to energy and CO_2 impacts due to direct energy consumption for transportation.[45] In addition to energy consumption for transportation of materials, energy is also needed to carry out on-site construction works. All such energy consumption activities were considered to estimate embodied energy and CO_2 impact on account of these activities.

With regard to materials and labour transportation, distance travelled is an important parameter for energy estimation. For the Rewari-Rohtak line, the average leads for material and labour transport ranged from 20 to 2,000 km (figure 4.4). Except sleepers and rails, all materials were transported by road-based modes like trucks, dumpers, tractor-trolleys, etc.; sleepers and rails were transported by rail rakes[46]. The number of trips for transportation of materials and labour were estimated based on quantities transported (figure 4.1) and average loading[47] on different modes and then used to estimate the diesel consumption.[48]

Figure 4.4 Average lead for materials and labour transportation



Source: Primary data collected by TERI from NRCO for Rewari-Rohtak rail line construction

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[45] As stated in the previous chapters, only the energy and CO_2 impacts of direct energy consumption for transportation are considered. Embodied energy and CO_2 of vehicles transporting materials/labour is not considered.

[46] For transport of materials by rail rakes, it is assumed that diesel locomotives were used.

[47] Average loading data was provided by NRCO.

[48] To and fro trips of vehicles have been considered while calculating fuel consumption i.e. if a truck is making a trip to transport cement to the site, diesel consumption has been estimated for it's to and fro trip (trip from cement factory to site and back to factory).

In addition to energy consumption for transport of materials and labour, energy is also consumed on construction site for various activities like rail welding, track tamping, etc. All such key energy consumption activities were considered to estimate the total energy consumption on-site.

Embodied energy and CO_2 due to energy consumption during construction

India-specific embodied energy coefficients[49] and CO_2 emission factors[50] for fuels were used.[51] The total embodied energy and CO_2 due to energy consumption for transportation of materials and labour and on-site energy needs (for construction of 1 km rail) are estimated to be about **0.52 TJ and 250 tonnes** respectively.

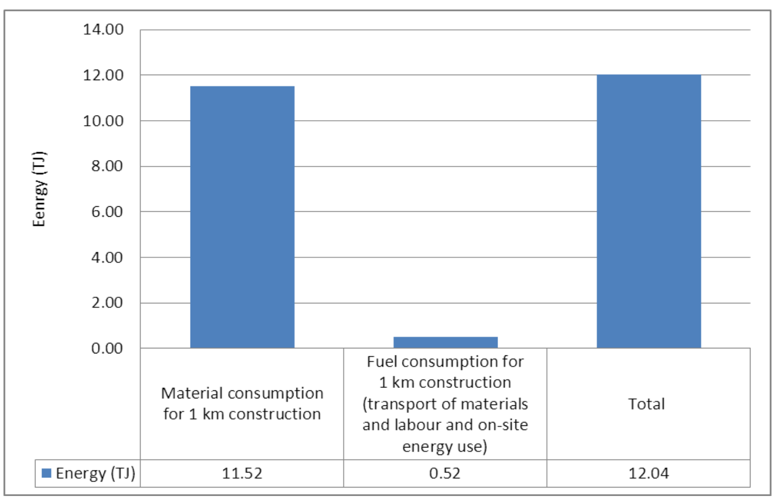
4.1.4 Removal of vegetation

As per discussions with NRCO, there wasn't any significant removal of vegetation in case of construction of Rohtak-Rewari line.

4.1.5 Summary construction phase - Embodied energy and CO_2

The embodied energy and CO_2 emissions estimated for construction of 1 km rail track are summarized in figures 4.5 and 4.6. Total embodied energy and CO_2 in constructing 1 km rail track are estimated at about **12 TJ and 1,300 tonnes**, respectively.

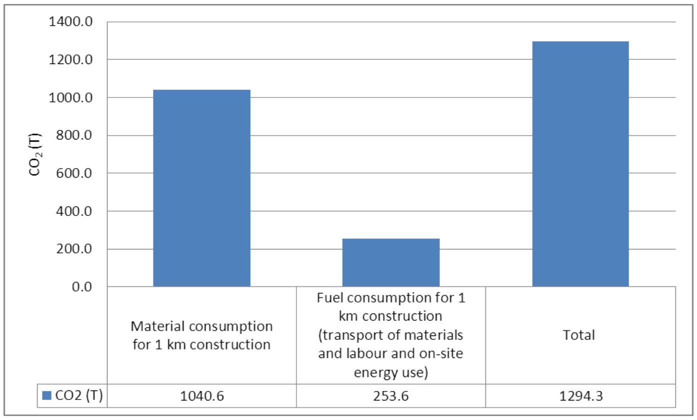
Figure 4.5 Long-distance rail - Embodied energy (TJ) per km construction



Source: Analysis by TERI

[49] Energy required to produce 1 unit of fuel.
[50] CO_2 emission factors used for fuels include embodied CO_2 in fuels i.e. CO_2 emitted to produce 1 unit of fuel and CO_2 at tail-pipe due to combustion of fuel.
[51] In case, India specific embodied energy coefficients were not available, the same were derived from international literature.

Figure 4.6 Long-distance rail - Embodied CO_2 (tonnes) per km construction



Source: Analysis by TERI

4.2 Maintenance

Maintenance of Delhi-Bathinda rail line was studied in order to estimate the embodied energy and CO_2 per kilometre (km) maintenance of a rail track. The details of Delhi-Bathinda section studied are given in the next section.

4.2.1 Project studied

Details of Delhi-Bathinda rail line are given in table 4.2. Maintenance data was collected from Delhi Division of Northern Railways (NR). It should be noted that Delhi-Bathinda line is a double line; the maintenance analysis hence represents embodied energy and CO_2 of a double line.

Table 4.2 Details of the rail maintenance project studied

Project:	**Delhi-Bathinda rail line maintenance (Double track)**		
State:	Delhi and Haryana		
Rail start and end points:	From- UP - 13.00 DN - 13.00	To- 295.56 199.43	Total distance- 282.56 km 186.43 km
Rail line construction year:	1897		
Design life of rails:	Depends on traffic conditions (Avg. life - 425 GMT or 15 years)		
Design life of sleepers:	Depends on traffic conditions (Avg. life PSC sleepers - 25 years)		

Source: Data provided by Delhi Division, NR

4.2.2 Annual routine maintenance

Annual maintenance data for 2010-11 was collected for the Delhi-Bathinda rail line. The key annual maintenance activities include:

- ERC greasing,
- Turnout maintenance (greasing of fittings and overhauling),
- Reconditioning of turnout,
- Through packing and overhauling of track,
- Spreading weedicide/de-weeding,
- Tamping,
- A.T. weld removal[52],
- Overhauling of level crossings, etc.

Annual material and energy consumption for the above listed activities was estimated with the help of data provided by Delhi Division of Northern Railways. Table 4.3 gives the quantities of key materials and fuels consumed for annual maintenance of Delhi-Bathinda line.

Table 4.3 Annual routine maintenance of rail line - Material consumption per km

Materials/fuels	Consumption per km maintenance (annual)
Grease	9.5 kg
Ballast	400.0 cum

Source: Data provided by Delhi Division, NR for Delhi-Bathinda rail line maintenance

The above consumption translates into **0.23 TJ embodied energy and 22 tonnes embodied CO_2**[53] annually.

4.2.3 Periodic maintenance (30 years duration)

There are several track maintenance activities like ballast/formation work (shallow/deep screening) that are not carried out annually but after an interval of few years. In addition, there are several components of a track that are replaced after few years. After discussions with officials of Delhi Division, the following periodic maintenance/renewal activities are assumed to take place during a 30 years period:

- Replacement of sleepers - once in 30 years
- Replacement of rails - twice in 30 years
- Ballast/formation work - through ballast renewal - twice in 30 years

[52] Data on gas used for welds was not available.

[53] Embodied energy and CO_2 of grease is not included due to unavailability of relevant coefficients.

The material consumption due to maintenance/renewal activities in 30 years period are given in table 4.4.

Table 4.4 Periodic maintenance/renewal of rail line (30 years period) - Material consumption per km

Track component	Material consumed	Quantity consumed per km (in 30 years)	Unit
Sleepers	Pre-stressed concrete	1,660	no.
Rail	Steel	208	tonnes
Ballast	Aggregate	5,000	cum
Blanket	Sand/moorum	8,400	cum
Track fittings and fastenings	Steel	27	tonnes

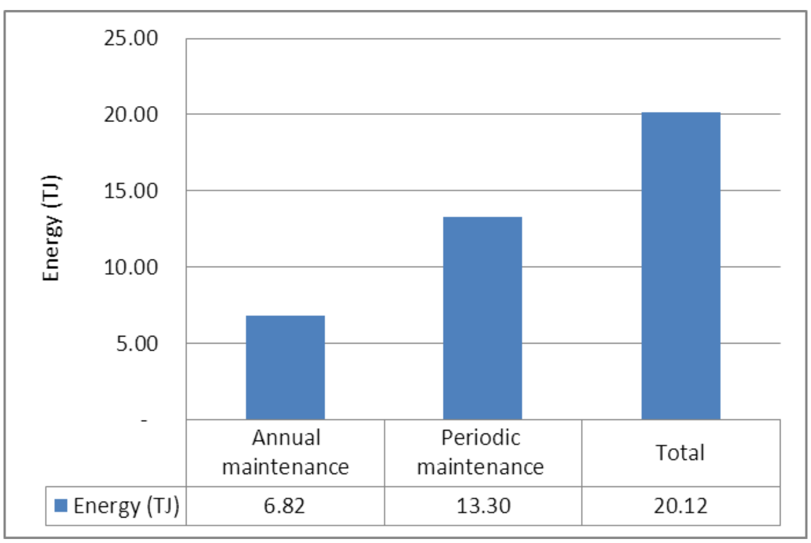
Source: Estimated based on discussions with Delhi Division officials of NR and new rail line construction data provided by NRCO

Consumption of materials for maintenance/renewal activities in 30 years period translates into **13.3 TJ embodied energy and 1,200 tonnes embodied CO_2**.

4.2.4 Summary maintenance phase - Embodied energy and CO_2

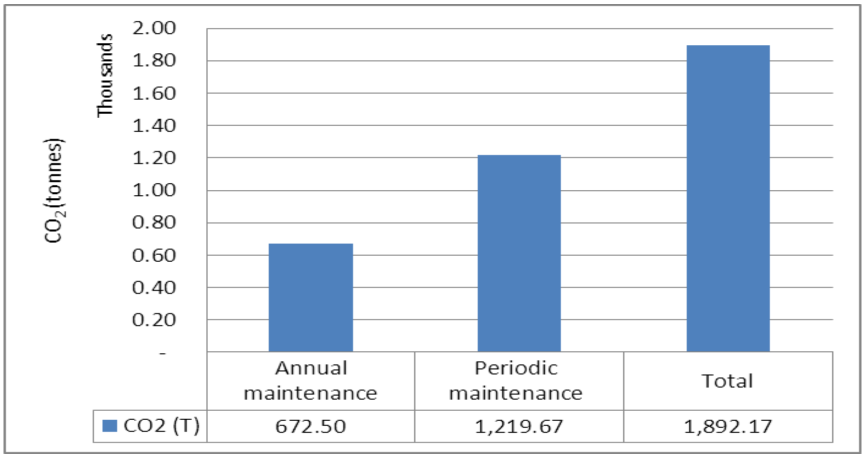
For a period of 30 years, annual routine maintenance and periodic maintenance/renewal activities translate into **embodied energy of about 20 TJ/km and embodied CO_2 of about 1,900 tonnes/km** (figures 4.7 and 4.8).

Figure 4.7 Maintenance of rail track for 30 years - Embodied energy (TJ) per km



Source: Analysis by TERI

Figure 4.8 Maintenance of rail track for 30 years - Embodied CO_2 (tonnes) per km



Source: Analysis by TERI

4.3 Operations

Operational energy consumption for Indian Railways was estimated by using fuel consumption data published in the Annual Statistical Statement (ASS), 2010-11 published by Indian Railways. While ASS provides data on total fuel consumption (electricity and diesel) for traction, it does not make distinction between passenger kms (PKM) by electricity and diesel traction. In order to estimate PKM by electric and diesel tractions, traction-wise vehicle kms data provided in ASS was used (table 4.5). It should be noted that operational energy consumption data for Railways was estimated for Broad Gauge (B.G.) only.

Table 4.5 Estimation of traction-wise PKM (non-suburban, B.G.)

	2009-10	2010-11
Total PKM (in thousands)[54]	744,131,219	807,458,400
Vehicle km (diesel traction) (in thousands)[55]	7,776,820	8,195,502
Vehicle km (electric traction) (in thousands)[56]	7,652,401	8,052,767
Total vehicle km (in thousands)	15,429,221	16,248,269
Proportion of diesel traction in total vehicle km	50.4%	50.4%
Proportion of electric traction in total vehicle km	49.6%	49.6%

[54] PKM of MEMU and DEMU (non-suburban) are not included

[55] Source: Annual Statistical Statement (ASS), 2010-11, Indian Railways; Vehicle km of MEMU and DEMU (non-suburban) are not included

[56] Ibid.

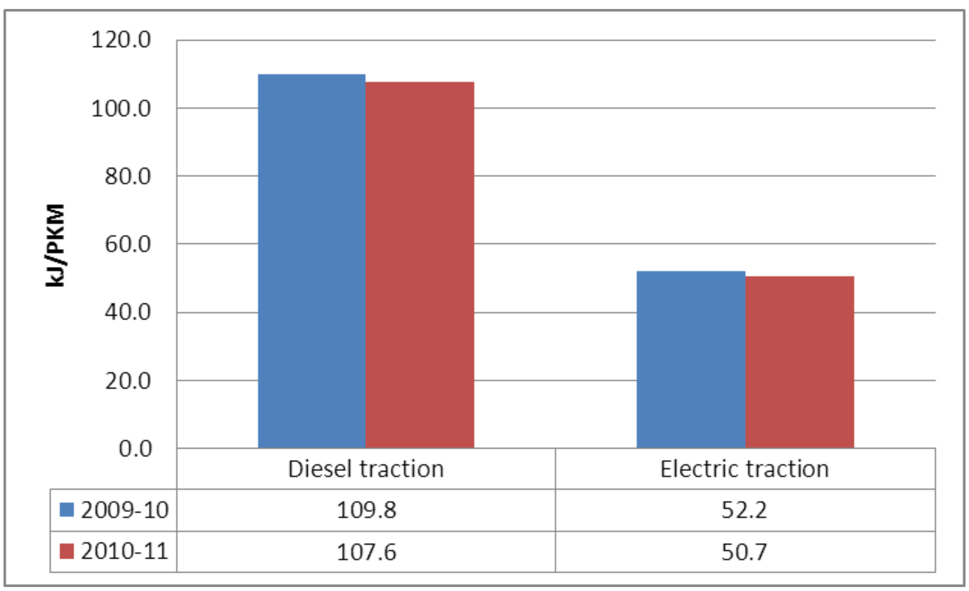
	2009-10	2010-11
Traction-wise (diesel and electric) PKM*		
PKM- Diesel Traction (in thousands)	375065893	407275811
PKM- Electric Traction (in thousands)	369065326	400182589
Total PKM (in thousands)	744131219	807458400

* Derived by applying the ratio of diesel and electric vehicle km to total PKM.

Source for traction-wise vehicle kms (B.G.) and total PKM data (B.G.): Annual Statistical Statement (ASS), 2010-11, Indian Railways

Traction-wise fuel consumption data from ASS and PKM data as estimated in table 4.5 was used to estimate energy consumption and CO_2 per PKM for Indian Railways operations (B.G.). For 2010-11, **operational energy consumption for B.G. was about 107.6 kJ/PKM for diesel traction and 50.7 kJ/PKM for electric traction** (figure 4.9). **CO_2 per PKM was 8.7 g/PKM and 11.4 g/PKM for diesel[57] and electric tractions, respectively** (figure 4.10).

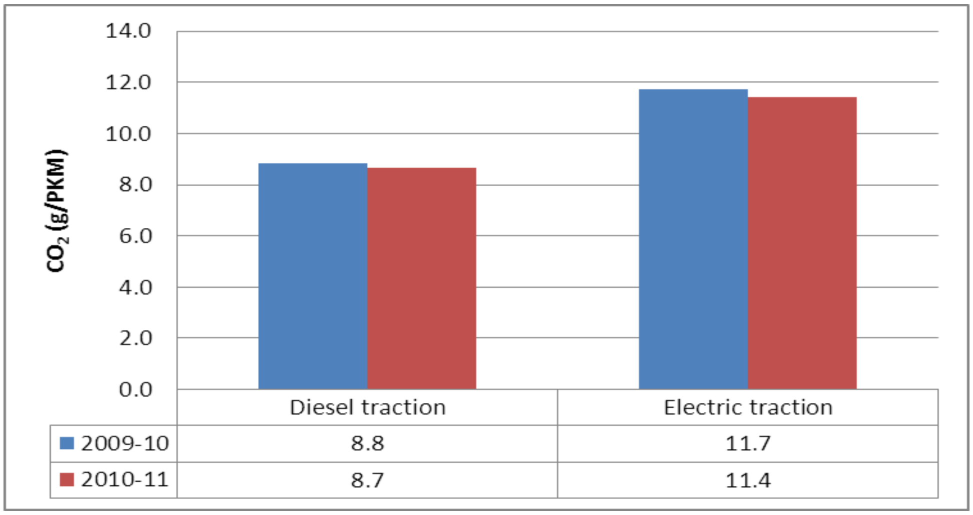
Figure 4.9 Operational energy consumption per PKM for Indian Railways (B.G.)



Source: Analysis by TERI

[57] Embodied CO_2 of diesel included.

Figure 4.10 Operational CO_2 emissions per PKM for Indian Railways (B.G.)



Source: Analysis by TERI

4.4 Embodied energy of rolling stock

As stated in the previous chapters, due to lack of data for India, international literature was reviewed to understand embodied energy and CO_2 values for rolling stock. Values estimated in Chester and Horvath (2009b) were considered. Table 4.6 gives the embodied energy and CO_2 values for rolling stock of Caltrain, San Francisco[58].

Figure 4.11 Caltrain, San Francisco[59]

[58] Regional rail based transit system (diesel traction). Bi-level gallery-type cars. 4 to 8 cars per train (http://www.caltrain.com/).

[59] http://pushingthepulldoor.blogspot.in/ and http://www.city-data.com/forum/city-vs-city/767822-san-francisco-las-vegas-what-would-9.html

Table 4.6 Embodied energy and CO_2 values (vehicle manufacture and maintenance) for rolling stock - Rail

Trains	Energy (TJ)		CO_2 (T)	
	Vehicle manufacture	Vehicle maintenance (full life)	Vehicle manufacture	Vehicle maintenance (full life)
Heavy rail - Caltrain, San Francisco	30 TJ/train (5 TJ/car)*	25 TJ/train (4.2 TJ/car)*	1,800 (300 T/car)*	1,100 (183.3 T/car)*

* Assuming an average of one locomotive and five cars per train

Source: Chester and Horvath (2009b)

4.5 Summary - Long-distance rail

Table 4.7 Life cycle embodied energy and CO_2 - Long-distance rail

Long-distance rail	Phase	Embodied energy	Unit	Embodied CO_2	Unit	Remarks
Fixed infrastructure	Construction	12.0	TJ/km	1,294.3	T/km	India-specific values, Based on TERI's analysis
	Maintenance (30years)	20.1	TJ/km	1,892.2	T/km	
Rolling stock	Manufacture	5.0	TJ/coach	300.0	T/coach	USA-specific values, Source: Chester and Horvath (2009b)
	Maintenance (full life)	4.2	TJ/coach	183.3	T/coach	
	Operations (diesel traction)	107.6	kJ/PKM	8.7	g/PKM	India-specific values, Based on TERI's analysis
	Operations (electric traction)	50.7	kJ/PKM	11.4	g/PKM	

Chapter 5: LCA results - Bus Rapid Transit System

5.1 Construction of BRTS corridor

Embodied energy and CO_2 per kilometre (km) construction of Bus Rapid Transit System (BRTS) was estimated by studying the construction of Ahmedabad BRTS. The details of the BRTS project studied are given in the next section.

5.1.1 Project studied

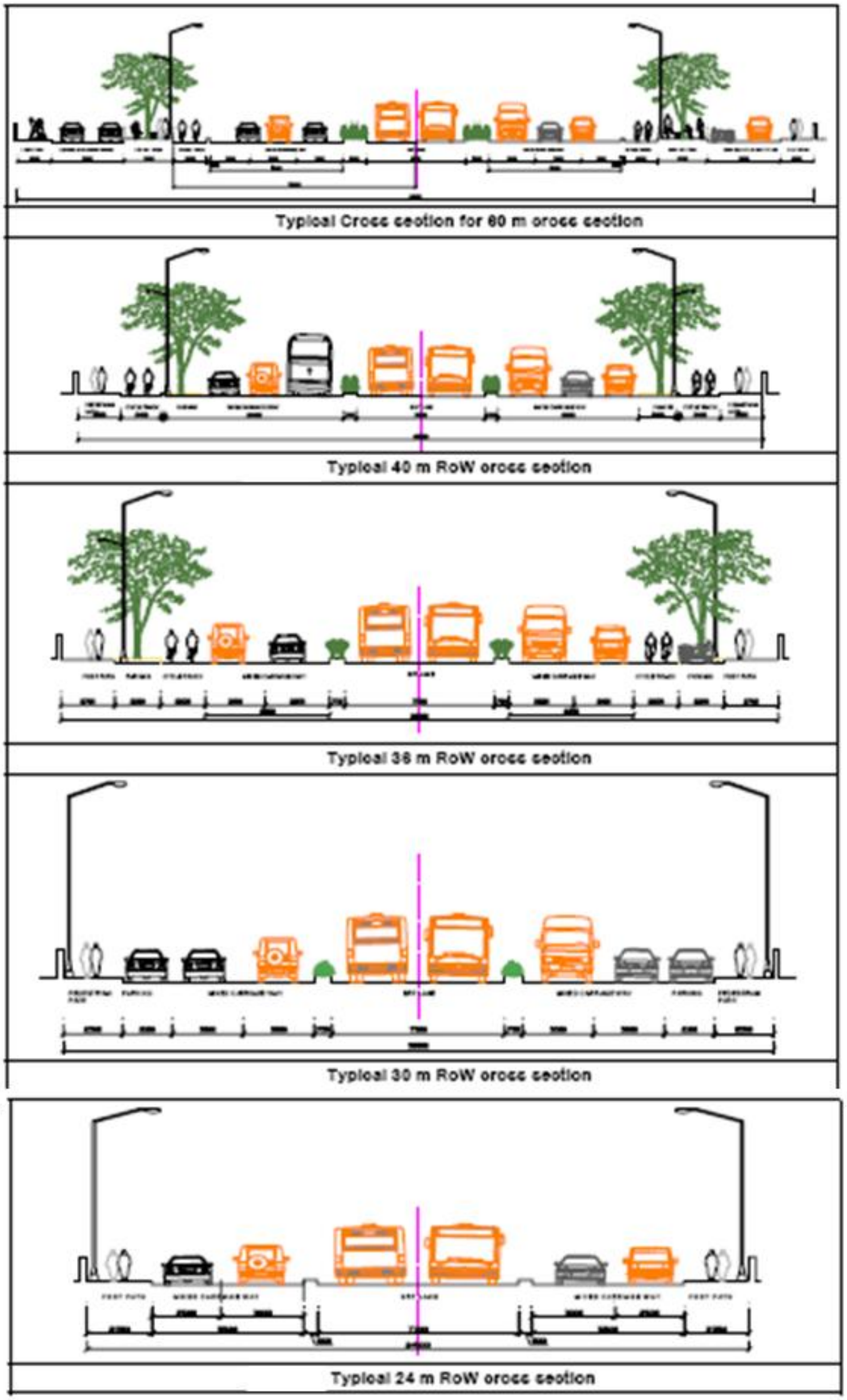
Construction of Ahmedabad BRTS was studied (Pirana–Danilimda–Maninagar–Narol stretch (12 km) and Narol-Naroda stretch (13.4 km)). The details about the project are given in table 5.1. Center for Environmental Planning and Technology University (CEPT), Ahmedabad provided data for the selected BRTS stretches.

Table 5.1 Details of the BRTS construction project studied

Project:	A total of 25.4 km of Ahmedabad BRTS construction covering: ▪ Pirana–Danilimda–Maninagar–Narol stretch (12 km) ▪ Narol-Naroda stretch (13.4 km)
City, State:	Ahmedabad, Gujarat
Total distance:	25.4 km
BRTS length constructed as on date when construction data was collected:	25.4 km
Construction duration:	Start date- 8th Aug, 2007 End date- 15th December, 2010
Design life of pavement (years):	Bus lane: 25 years Private vehicle lane: 25 years Cycle track: 25 years Footpath: 5 years
Cross-section details	ROW varies from 25 m to 60 m (Typical cross-sections shown in figure 5.1)

Source: Data provided by CEPT

Figure 5.1 Typical cross-sections for ROW 60m, 40m, 36m, 30m, and 24m, Ahmedabad BRTS



Source: Ahmedabad BRTS Detailed Project Report, 2008

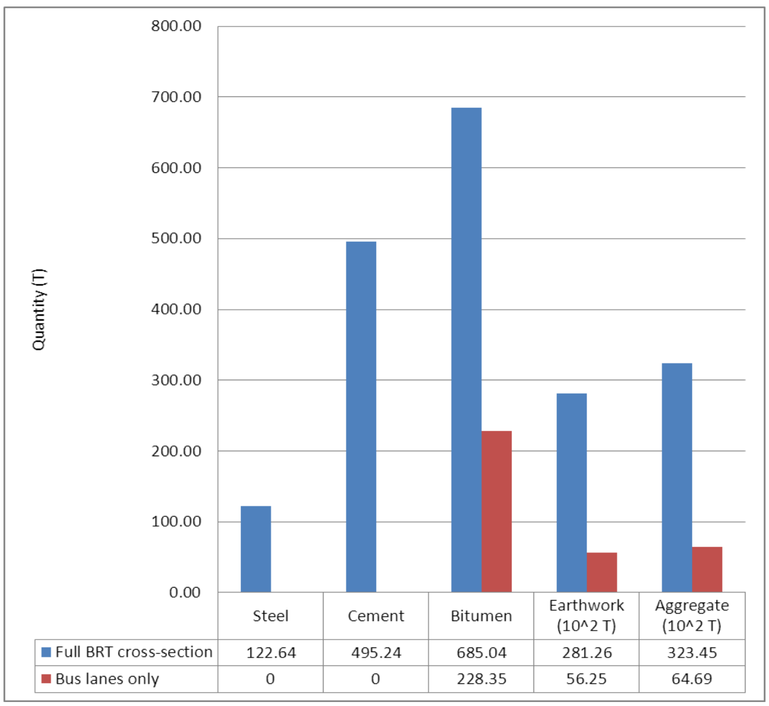
5.1.2 Consumption of materials during construction

Key materials consumed for BRTS construction include:

- Aggregate
- Bitumen
- Bitumen emulsion
- Cement
- Steel
- Earth
- Bricks

Per kilometre consumption of key materials in construction of BRTS is given in figure 5.2.

Figure 5.2 Consumption of key materials- 1 km BRTS construction



Source: Primary data collected by TERI from CEPT for Ahmedabad BRTS

About 685 tonnes of bitumen was consumed per km for construction of Ahmedabad BRTS corridor; of which about 228 tonnes was consumed for construction the bus lanes. Construction also involved significant consumption of aggregates (coarse/fine); about 32 thousand tonnes of aggregates were consumed per km (about 6.5 thousand tonnes were used just for the bus lanes). Earthwork to the tune of about 28 thousand tonnes per km was carried out for the whole BRT cross-section. The other key materials used for construction of BRTS included steel (122 tonnes/km) and cement (495 tonnes/km).

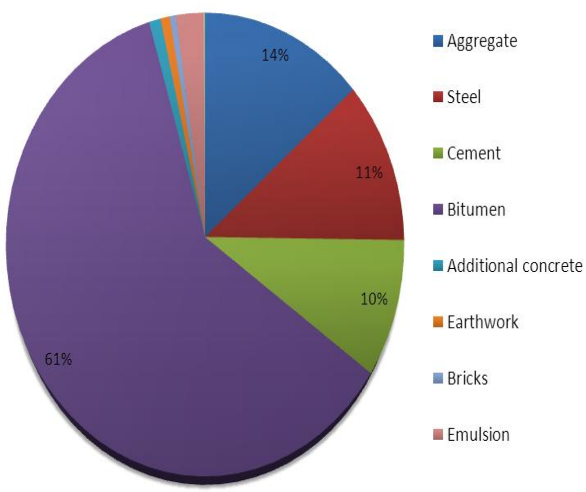
Embodied energy and CO_2 due to material consumption

Embodied energy and CO_2 of materials consumed per km was estimated by using India-specific embodied energy and CO_2 coefficients for materials.[60] The embodied energy and CO_2 of materials used per km **BRTS construction (full cross-section)** are estimated to be about **51 TJ and 2,120 tonnes**, respectively. For **only the bus lanes**, the embodied energy and CO_2 due to material consumption per km are estimated to be about **12.3 TJ and 371.7 tonnes**, respectively.

In the construction of full BRTS cross-section, bitumen has the maximum contribution (61%) to the embodied energy of per km materials used (figure 5.3). As stated in the section on National Highways, the embodied energy of bitumen is very high as compared to that of aggregates.[61] Therefore, comparatively much lesser consumption of bitumen (685 tonnes/km) as compared to aggregates (28,000 tonnes/km) leads to much higher embodied energy per km (Bitumen: 31 TJ/km; Aggregates: 7 TJ/km). Also, extensive earthwork (32,000 tonnes/km) contributes very less embodied energy per km (0.4 TJ; <1%) as the embodied energy per tonne earthwork is comparatively very low[62]. Use of steel and cement contributes about 21% embodied energy. In case of embodied CO_2 per km materials used, aggregates have the maximum contribution of about 32%, followed by steel (27%), cement (21%) and bitumen[63] (15%) (figure 5.4).

In the construction of only the bus lanes of the BRTS corridor, bitumen and aggregate have the maximum contribution to embodied energy and CO_2 (figures 5.5 and 5.6).

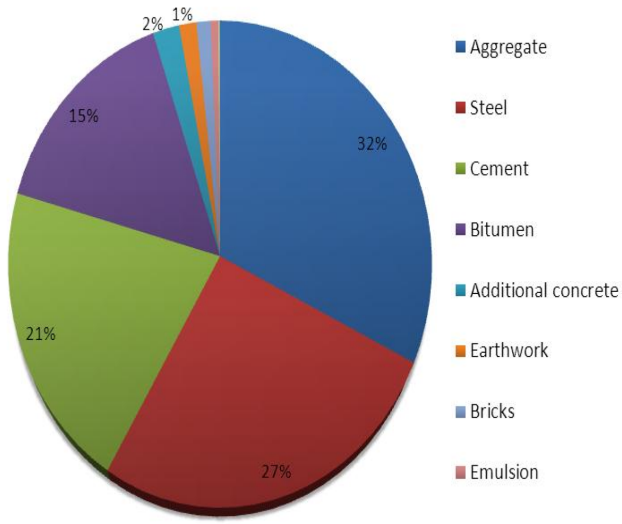
Figure 5.3 Contribution of different materials to embodied energy of materials used per km construction of full cross-section of BRTS corridor



Source: Analysis by TERI

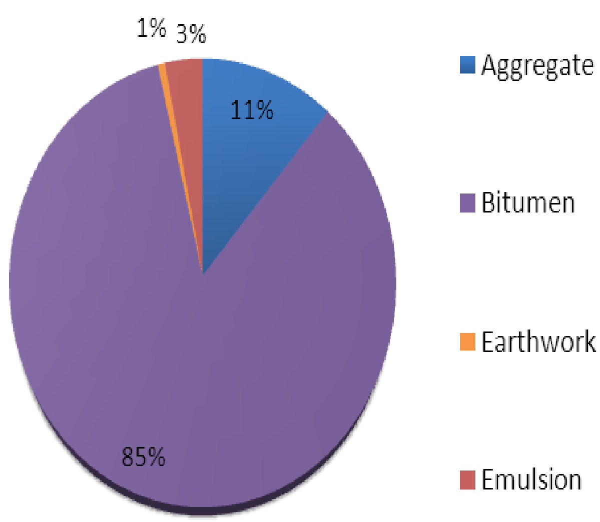
[60] In case, India specific embodied energy coefficients were not available for some materials, the same were derived from international literature.
[61] Embodied energy - Bitumen: 44.70 MJ/kg, Coarse aggregate: 0.22 MJ/kg, Fine aggregate (sand): 0.02 MJ/kg
[62] Embodied energy - Earthwork: 0.01 MJ/kg
[63] Bitumen has high contribution in embodied energy (61%), but not in embodied CO_2 (15%). This is because bitumen has a very high embodied energy coefficient (44.7 MJ/kg), which is more than 200 times higher than coarse aggregate. Embodied CO_2 coefficient of bitumen is 0.48 kg CO_2/kg bitumen, only about 20 times more than coarse aggregate (0.02 kg CO_2/kg aggregate).

Figure 5.4 Contribution of different materials to embodied CO_2 of materials used per km construction of full cross-section of BRTS corridor



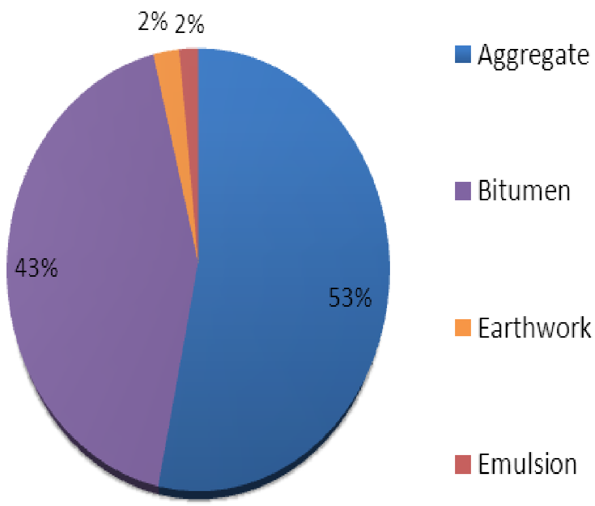
Source: Analysis by TERI

Figure 5.5 Contribution of different materials to embodied energy of materials used per km construction of bus lanes only



Source: Analysis by TERI

Figure 5.6 Contribution of different materials to embodied CO_2 of materials used per km construction of bus lanes only



Source: Analysis by TERI

5.1.3 Energy consumption during construction - Transportation of materials and labour and on-site energy consumption

Embodied energy and CO_2 due to transportation of materials/labour[64] and on-site energy consumption was estimated using data collected for Ahmedabad BRTS. Average lead of materials and labour transportation ranged from 5 to 800 km (figure 5.7). Data on number of trips[65] performed by trucks, tankers, dumpers, etc. was collected; this data was used to estimate the fuel consumption for transportation. Data for on-site energy consumption in the form of electricity, diesel, petrol, furnace oil, LDO, and kerosene was also collected to estimate embodied energy and CO_2 due to this energy consumption. Table 5.2 gives the total energy consumption for transportation of materials/labour and on-site construction processes (for construction of full cross-section of BRTS).

Table 5.2 Total energy consumption for transportation of materials/labour and on-site construction processes (for construction of full cross-section of BRTS)

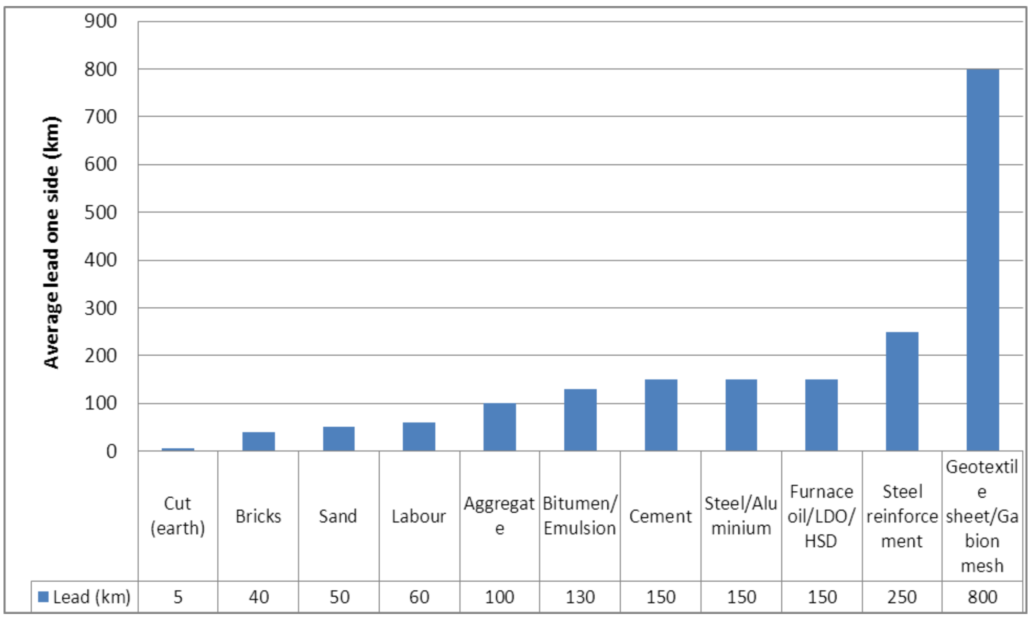
Energy/fuel type	Unit	Quantity consumed per km
Electricity	kWh	1,574.80
Diesel	GJ	3,689.47

[64] Only the energy and CO_2 impacts of direct energy consumption for transportation are considered. Embodied energy and CO_2 of vehicles transporting materials/labour is not considered.
[65] To and fro trips of vehicles have been considered while calculating fuel consumption i.e. if a truck is making a trip to transport cement to the site, diesel consumption has been estimated for it's to and fro trip (trip from cement factory to site and back to factory).

Energy/fuel type	Unit	Quantity consumed per km
Petrol	GJ	0.13
Furnace oil	GJ	2,620.97
LDO	GJ	899.22
Kerosene	GJ	0.14

Source: Primary data collected by TERI from CEPT for Ahmedabad BRTS

Figure 5.7 Average lead for materials and labour transportation



Source: Primary data collected by TERI from CEPT for Ahmedabad BRTS

Embodied energy and CO_2 due to energy consumption during construction

India-specific embodied energy coefficients[66] and CO_2 emission factors[67] for fuels like diesel, LDO, kerosene, etc. were used.[68] The total embodied energy and CO_2 due to energy consumption for transportation of materials and labour and on-site energy needs (for construction of 1 km BRTS) are estimated to be about **1.2 TJ and 580 tonnes,** respectively.

[66] Energy required to produce 1 unit of fuel.

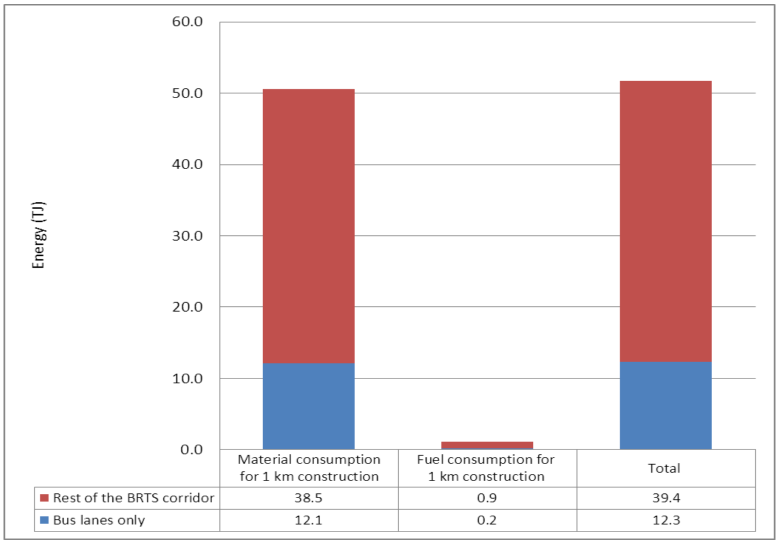
[67] CO_2 emission factors used for fuels include embodied CO_2 in fuels i.e. CO_2 emitted to produce 1 unit of fuel and CO_2 at tail-pipe due to combustion of fuel.

[68] In case, India specific embodied energy coefficients were not available, the same were derived from international literature.

5.1.4 Summary construction phase (1 km BRTS corridor) - Embodied energy and CO_2

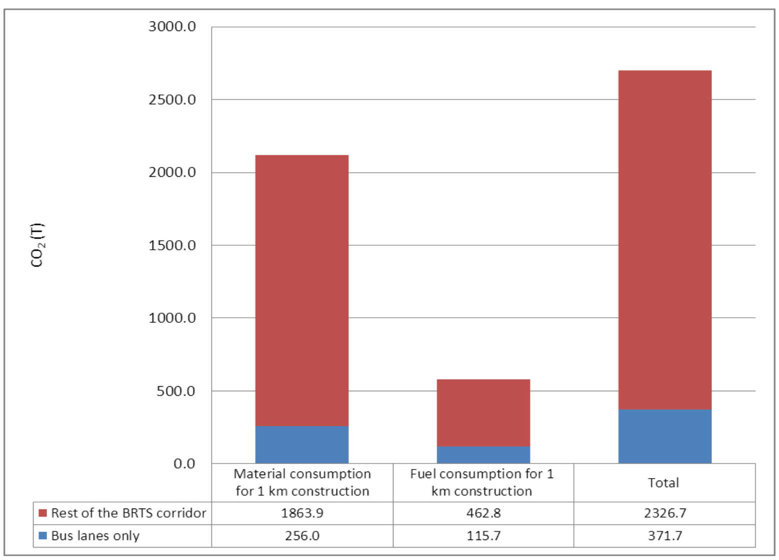
The embodied energy and CO_2 emissions estimated for construction of 1 km BRTS are summarized in figures 5.8 and 5.9. Total embodied energy and CO_2 in constructing 1 km BRTS are estimated at about **52 TJ and 2,700 tonnes**, respectively. Construction of only the **bus lanes** leads to embodied energy and CO_2 of about **12.3 TJ and 371.7 tonnes**, respectively.

Figure 5.8 BRTS - Embodied energy (TJ) per km construction



Source: Analysis by TERI

Figure 5.9 BRTS - Embodied CO_2 (tonnes) per km construction



Source: Analysis by TERI

5.2 Construction of BRTS station

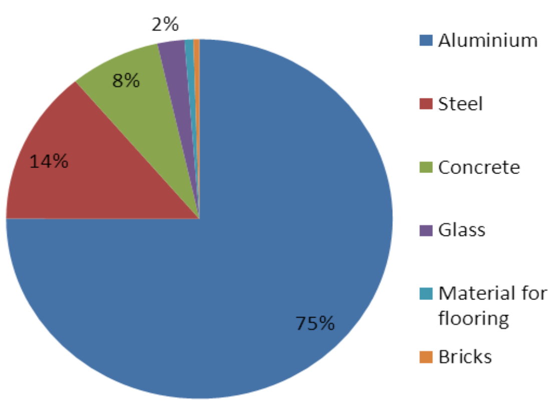
In addition to estimating embodied energy and CO_2 of 1 km BRTS stretch, embodied energy and CO_2 of one BRTS station were also estimated. Key materials consumed for constructing a BRTS station were considered and converted into equivalent energy and CO_2[69]. Table 5.3 gives the quantities of key materials consumed for constructing a typical BRTS station of Ahmedabad BRTS. Consumption of these materials translates into **embodied energy of about 3.6 TJ and embodied CO_2 equivalent to about 345 tonnes per BRTS station**. Use of aluminium in BRTS stations constitutes to maximum embodied energy (about 75%) among all materials used for station construction. Other key contributors include steel (14%) and concrete (8%) (figure 5.10).

Table 5.3 Key materials consumed in construction of one typical BRTS station

Materials	Quantity	Unit
Concrete	110.0	cum
Steel	11.0	tonnes
Bricks	8.0	cum
Structural steel	4.0	tonnes
Glass	3.1	tonnes
Stone	6.0	cum
China mosaic	5.8	tonnes
Aluminium	10.4	tonnes

Source: Primary data collected by TERI from CEPT for Ahmedabad BRTS

Figure 5.10 Contribution of different materials to embodied energy of materials used for construction of a typical BRTS station



Source: Analysis by TERI

[69] Only material consumption was considered in estimating embodied energy and CO_2 of BRTS station.

5.3 Maintenance

Maintenance of Ahmedabad BRTS was studied in order to estimate the embodied energy and CO_2 per kilometre (km) maintenance of BRTS. The details of Ahmedabad BRTS are given in the next section.

5.3.1 Project studied

Maintenance of Ahmedabad BRTS' operational sections was studied. The details about the project are given in table 5.4. CEPT, Ahmedabad provided the data.

Table 5.4 Details of the Ahmedabad BRTS corridor studied for maintenance data

Project:	**Maintenance of Ahmedabad BRTS:** ▪ **Pirana–Danilimda–Maninagar–Narol stretch (12 km)** ▪ **Narol-Naroda stretch (13.4 km)**
City, State:	Ahmedabad, Gujarat
BRTS length for which maintenance data was collected:	25.4 km
BRTS construction completion date:	December 2010
Design life of pavement (years):	Bus lane: 25 years Private vehicle lane: 25 years Cycle track: 25 years Footpath: 5 years
Cross-section details	ROW varies from 25 m to 60 m (Typical cross-sections shown in figure 5.1)

Source: Data provided by CEPT

5.3.2 Annual routine maintenance

Annual routine maintenance works in case of Ahmedabad BRTS mainly involve patch repairs, as and when required. About 25 tonnes of bitumen was used for annual maintenance between Dec 2010-11. This translates into **0.06 TJ embodied energy and 3.5 tonnes embodied CO_2 per km** annually[70] (**Bus lanes only- 0.02 TJ embodied energy and 3.5 tonnes embodied CO_2** per km annually).

[70] As stated in previous chapters, only material consumption is considered while estimating embodied energy and CO_2 of maintenance activities (annul and periodic).

5.3.3 Periodic maintenance (30 years duration)

Since, Ahmedabad BRTS' construction was completed in 2010; it will require periodic renewal after a few years. Assumptions were hence made to estimate material consumption for periodic maintenance of Ahmedabad BRTS. Key assumptions are:

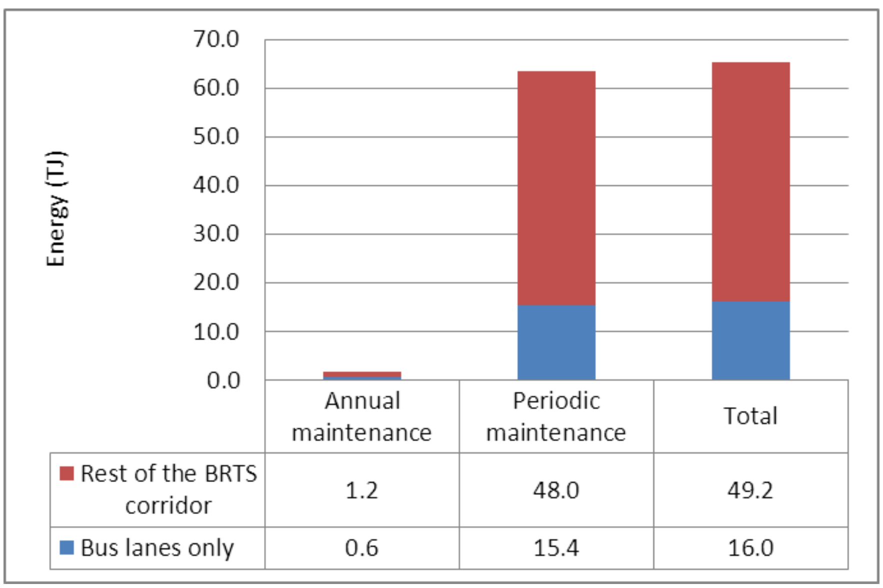
- BRTS will require periodic renewal after every 7 years
- One periodic renewal will require about one-third of the materials (primarily bitumen) used during original construction of the BRTS[71]

Based on these assumptions, it is estimated that consumption of materials for periodic renewal of BRTS in 30 years period will translate into **64 TJ embodied energy and 2,340 tonnes embodied CO_2 (Bus lanes only- 15 TJ embodied energy and 411 tonnes embodied CO_2** per km).

5.3.4 Summary maintenance phase - Embodied energy and CO_2

Annual routine maintenance and periodic maintenance/renewal for a 30 year period translates into **embodied energy of about 65 TJ and embodied CO_2 of about 2,450 tonnes per km** (figures 5.11 and 5.12).

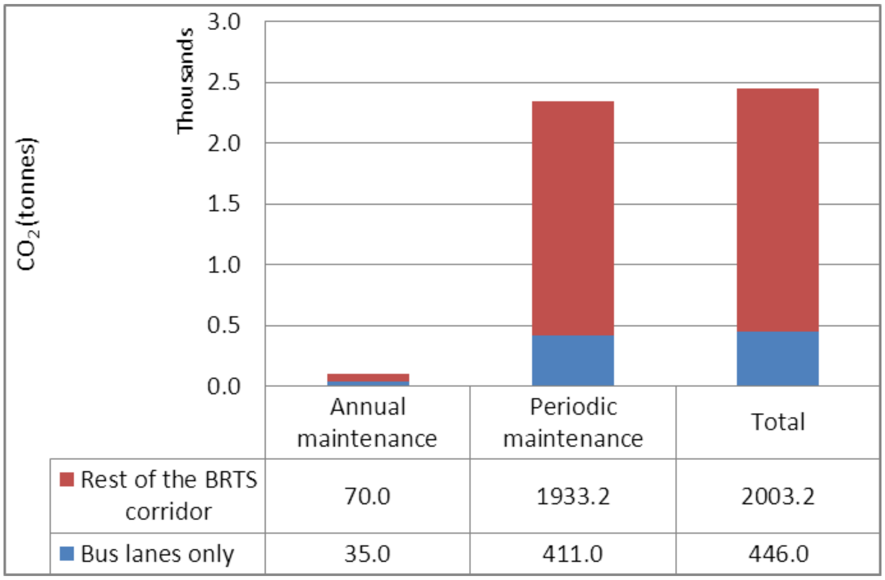
Figure 5.11 Maintenance of BRTS for 30 years - Embodied energy (TJ) per km



Source: Analysis by TERI

[71] TERI's analysis of periodic maintenance of an urban road in Delhi indicated that one periodic renewal of an urban road requires about one third material consumption as compared to construction. The data/estimations are discussed in Chapter 10 on 'LCA results: Urban road'. This was taken as a basis for periodic maintenance activity for BRTS.

Figure 5.12 Maintenance of BRTS for 30 years - Embodied CO_2 (tonnes) per km



Source: Analysis by TERI

5.4 Operations

Data for operational energy consumption of Ahmedabad BRTS was provided by CEPT. Table 5.5 shows the estimations done to derive energy consumption and CO_2 emissions per PKM for Ahmedabad BRTS. **Average energy consumption and CO_2 for Ahmedabad BRTS for its operations as on today are estimated to be around 554.1 kJ/PKM and 44.6 g/PKM**, respectively. For BRTS operations in 2014, the operational **energy consumption and CO_2 are estimated to be around 458.1 kJ/PKM and 36.9 g/PKM**, respectively.

Table 5.5 Operational energy consumption per PKM and CO_2 per PKM of Ahmedabad BRTS

		By March 2012	By March 2014	Remarks
A	BRTS operations (km)	44	129	Source: Data provided by CEPT
B	Passenger per km per day	3100	8000	
C	Total passengers per day	136400	1032000	=(A*B)
D	Average lead (km)	6.2	7.5	Source: Data provided by CEPT
E	PKM per day	845680	7740000	=(C*D)
F	Passengers per bus per day	1400	1400	Source: Data provided by CEPT

		By March 2012	By March 2014	Remarks
G	No. of buses	97	737	=(C/F)
H	km per bus per day	260	260	Source: Data provided by CEPT
I	Total bus kms	25331.4	191657.1	=(G*H)
J	Fuel efficiency			
	AC bus (km/l)	2	2	Source: Data provided by CEPT
	AC bus (km/l)	4.25	4.25	Assumed based on ASRTU data
K	Fuel consumption per day (l)			
	AC bus	12665.7	95828.6	=(1/J)*I
	Non-AC bus	5960.3	45095.8	
L	Fuel consumption per day (MJ)			
	AC bus	468631.4	3545657.1	1 liter diesel = 37 MJ
	Non-AC bus	220532.4	1668544.5	
M	MJ/PKM			
	AC bus	0.554	0.458	=(L/E)
	Non-AC bus	0.261	0.216	
O	CO_2 (kg/PKM)			CO_2 emission factor of diesel = 0.0805 kg/MJ (Well to tank to tailpipe CO_2 emission factor)
	AC bus	0.045	0.037	
	Non-AC bus	0.021	0.017	

5.5 Embodied energy of rolling stock

Rolling stock of BRTS i.e. buses have embodied energy and CO_2 on account of manufacturing and maintenance processes[72]. As indicated in previous chapters, values from international literature were used to understand embodied energy and CO_2 values for rolling stock. Table 5.6 gives the values for buses in USA.

[72] End-of-life embodied energy and CO_2 of rolling stock are not considered as dismantling/recycling vehicles are not widely adopted practices in Indian context.

Table 5.6 Embodied energy and CO_2 values (vehicle manufacture and maintenance) for rolling stock - Bus

Buses	Energy (TJ)		CO2 (T)	
	Vehicle manufacture	Vehicle maintenance (full life)	Vehicle manufacture	Vehicle maintenance (full life)
Diesel bus (1)	2.0	0.3	160.0	22.0
Diesel bus (2)	1.7	0.3	140.0	22.0

Source: Chester and Horvath (2009b)

5.6 Summary - BRTS

Table 5.7 Life cycle embodied energy and CO_2 - BRTS

BRTS	Phase	Embodied energy	Unit	Embodied CO_2	Unit	Remarks
Fixed infrastructure	Construction					India-specific values, Based on TERI's analysis
	1 km corridor	51.7	TJ/km	2,698.4	T/km	
	I km bus lanes only	12.3	TJ/km	371.7	T/km	
	I bus stop	3.6	TJ/stop	346.8	T/stop	
	Maintenance[73] (30years)					
	1 km corridor	65.3	TJ/km	2,449.2	T/km	
	I km bus lanes only	16.0	TJ/km	446.0	T/km	
Rolling stock	Manufacture	1.7	TJ/bus*	140.0	T/bus*	USA-specific values, Source: Chester and Horvath (2009b)
	Maintenance (full life)	0.3	TJ/bus*	22.0	T/bus*	
	Operations 2012**	544.1	kJ/PKM	44.6	g/PKM	India-specific values, Based on TERI's analysis
	Operations 2014 **	458.1	kJ/PKM	36.9	g/PKM	

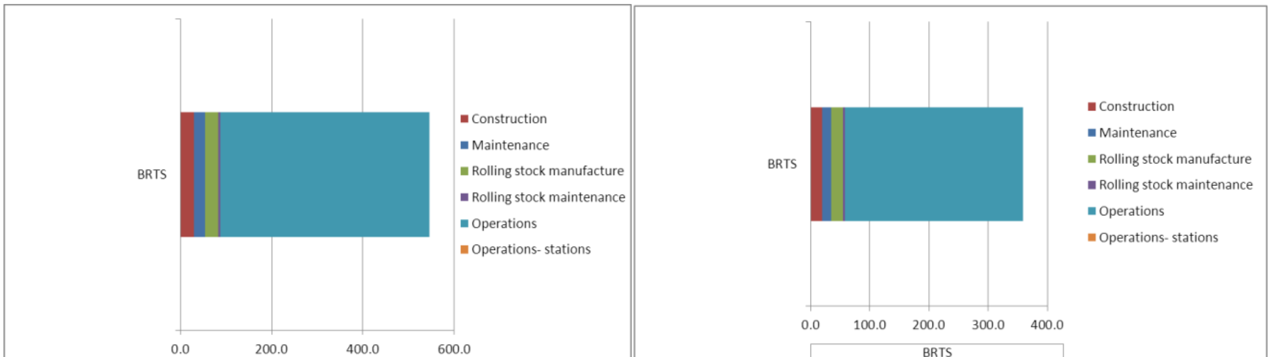
*Diesel bus **AC diesel bus

73 Only maintenance of corridor considered; maintenance of station not included.

5.7 Application of LCA results for BRTS

The LCA results derived in the previous sections have been applied to the Ahmedabad BRTS project[74] to estimate the full life cycle impacts of the project on a per PKM and per km basis. The assumptions, data, etc. used for the calculations are given in Annexure 1. The results are summarized in figures 5.13 and 5.14.

Figure 5.13 Ahmedabad BRTS - Life cycle energy consumption per PKM and per km



	BRTS
Construction	29.3
Maintenance	24.4
Rolling stock manufacture	29.6
Rolling stock maintenance	4.7
Operations	458.1
Operations- stations	0.0

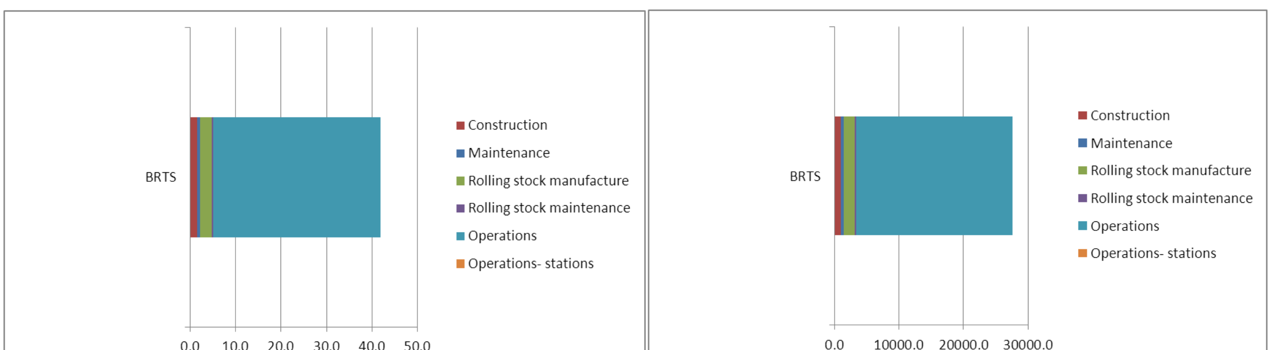
Energy - kJ/PKM

	BRTS
Construction	19.3
Maintenance	16.0
Rolling stock manufacture	19.4
Rolling stock maintenance	3.1
Operations	301.0
Operations- stations	0.0

Energy - TJ/km

Source: Analysis by TERI

Figure 5.14 Ahmedabad BRTS - Life cycle CO_2 emissions per PKM and per km



	BRTS
Construction	1.6
Maintenance	0.7
Rolling stock manufacture	2.4
Rolling stock maintenance	0.4
Operations	36.9
Operations- stations	0.0

CO_2 - g/PKM

	BRTS
Construction	1041.2
Maintenance	446.0
Rolling stock manufacture	1600.0
Rolling stock maintenance	251.4
Operations	24228.0
Operations- stations	0.0

CO_2 - T/KM

Source: Analysis by TERI

[74] Estimation done for the total BRTS project in Ahmedabad (129 km), which is expected to be fully operational by 2014. The system has been assumed to run to its full capacity. Only bus lanes have been considered for the construction and maintenance components.

Chapter 6: LCA results - Metro rail

6.1 Construction of Metro rail track[75]

Construction of Delhi Metro's New Ashok Nagar-Noida line was studied in order to estimate embodied energy and CO_2 per km track construction. Details of the Metro line studied are given in the next section.

6.1.1 Project studied

Construction of Metro line from New Ashok Nagar to Sector 32, Noida (7.2 km) was studied. The details about the project are given in table 6.1. Data on construction details of this project was provided by Delhi Metro Rail Corporation (DMRC).

Table 6.1 Details of the metro construction project studied

Name of the project:	**Delhi Metro Rail project**		
City:	New Delhi		
Metro rail start and end points:	From- New Ashok Nagar (Delhi)	To- Sector 32 (Noida)	Total distance between the two points (km): 7.2 kms
Construction duration:	Start date- August, 2006 End date- November, 2009		
Design life of rails: **Design life of viaduct:**	30 years 100 years		
Cross-section details:	Box girder with top slab width of girder - 9.1 m, height of box girder- 2.25 m, height of rail level above the existing road level - 9.8 m		

Source: Data provided by DMRC

6.1.2 Consumption of materials during construction

Key materials consumed[76] for Metro line construction include:

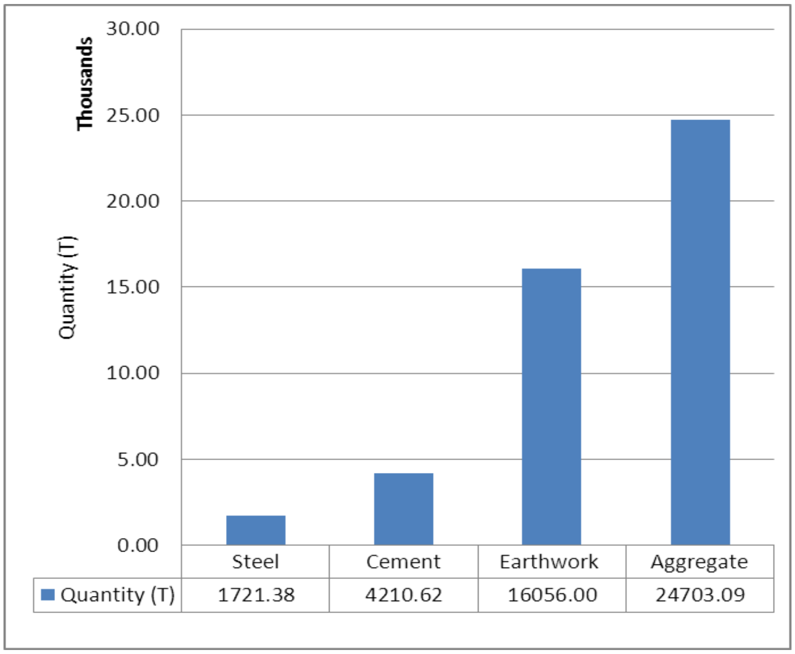
- Aggregate
- Cement
- Steel
- Earth

[75] Elevated track considered

[76] Consumption of materials for signalling works is not included in the LCA analysis

Per kilometre consumption of key materials in construction of Metro line is given in figure 6.1.

Figure 6.1 Consumption of key materials- 1 km Metro line construction



Source: Primary data collected by TERI from DMRC for Delhi Metro

Construction of elevated metro line involves significant consumption of steel and cement per km, both of which are highly energy and carbon intensive materials. In the construction of 1 km elevated line between New Ashok Nagar and Sector 32 (Noida), about 1,720 tonnes of steel and 4,210 tonnes of cement were used per km. Consumption of aggregates was to the tune of about 25 thousand tonnes per km. About 16 thousand tonnes of earthwork was carried out per km.

Embodied energy and CO_2 due to material consumption

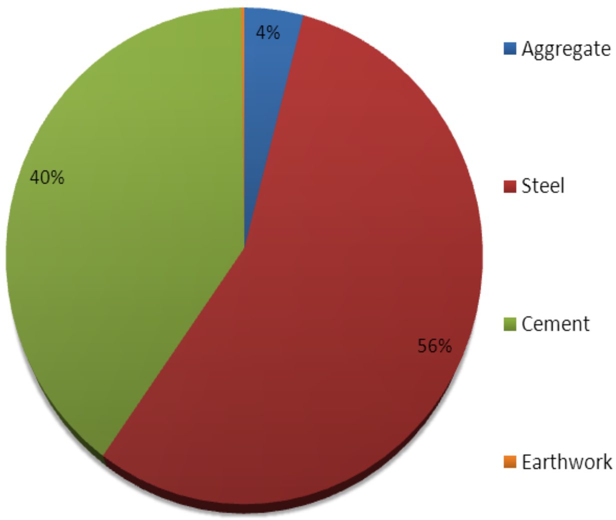
Embodied energy and CO_2 of materials consumed per km was estimated by using India-specific embodied energy and CO_2 coefficients for materials.[77] The embodied energy and CO_2 of materials used per km Metro line construction is estimated to be about **103 TJ and 9,300 tonnes**, respectively.

Steel has the maximum contribution (56%) to the embodied energy and CO_2 per km materials used (figures 6.2 and 6.3). Cement and aggregate contribute about 40% and 4%, respectively to embodied energy and CO_2. While aggregates consumption and earthwork carried out per km are very high (figure 6.1), their contribution to embodied energy and CO_2 per km materials used is low (<5%) due to their comparatively low embodied energy and CO_2 coefficients.[78]

[77] In case, India specific embodied energy coefficients were not available for some materials, the same were derived from international literature.

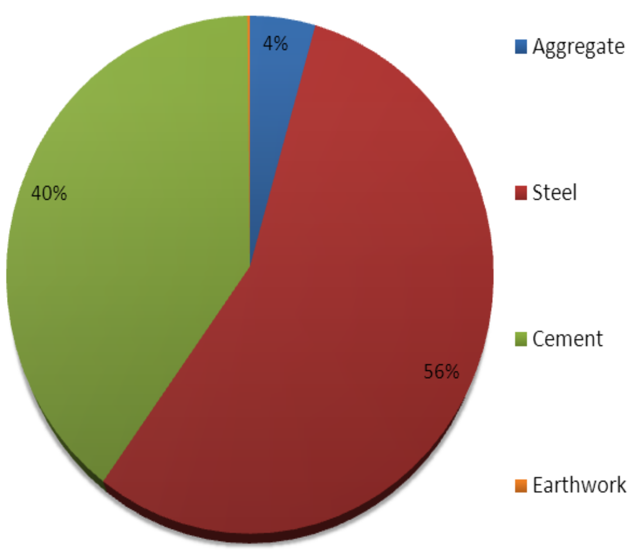
[78] Embodied energy coefficients- Coarse aggregate: 0.22 MJ/kg; Fine aggregate: 0.02 MJ/kg; Steel: 33.33 MJ/kg; Cement: 9.78 MJ/kg. CO_2 emission factors- Coarse aggregate: 0.02 kg/kg; Fine aggregate: 0.002 kg/kg; Steel: 3.0 kg/kg; Cement: 0.88 kg/kg

Figure 6.2 Contribution of different materials to embodied energy of materials used per km Metro line construction



Source: Analysis by TERI

Figure 6.3 Contribution of different materials to embodied CO_2 of materials used per km Metro line construction

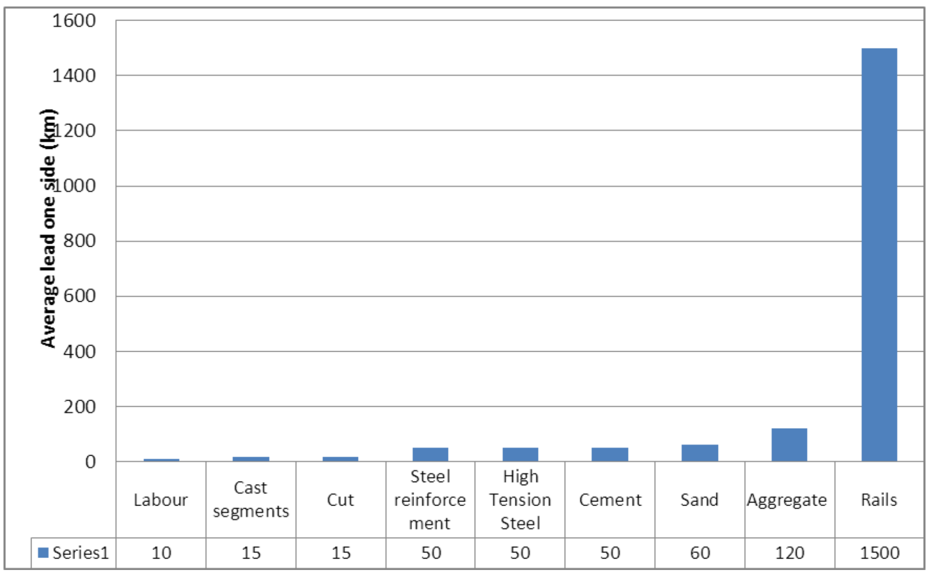


Source: Analysis by TERI

6.1.3 Energy consumption during construction - Transportation of materials and labour and on-site energy consumption

Embodied energy and CO_2 due to transportation of materials/labour[79] and on-site energy consumption was estimated using data collected from DMRC. Average lead of materials and labour transportation ranged from 10 to 1,500 km (figure 6.4). Data on quantities transported (figure 6.1) and average loading[80] per vehicle was used to estimate the number of trips[81], which were then converted to equivalent vehicle kms by considering average leads for different materials and vehicle types (trucks, trailers, rail, dumpers, transit mixers, etc.). Fuel consumption for this entire material/labour transport was then estimated. Data for on-site energy consumption for running machinery and equipments like piling ring, excavators, mobile cranes, etc. was also collected from DMRC.[82] About 240 kilolitres (kl) diesel was consumed per km for transport of materials/labour and for meeting on-site energy needs.

Figure 6.4 Average lead for materials and labour transportation



Source: Primary data collected by TERI from DMRC for Delhi Metro

Embodied energy and CO_2 due to energy consumption during construction

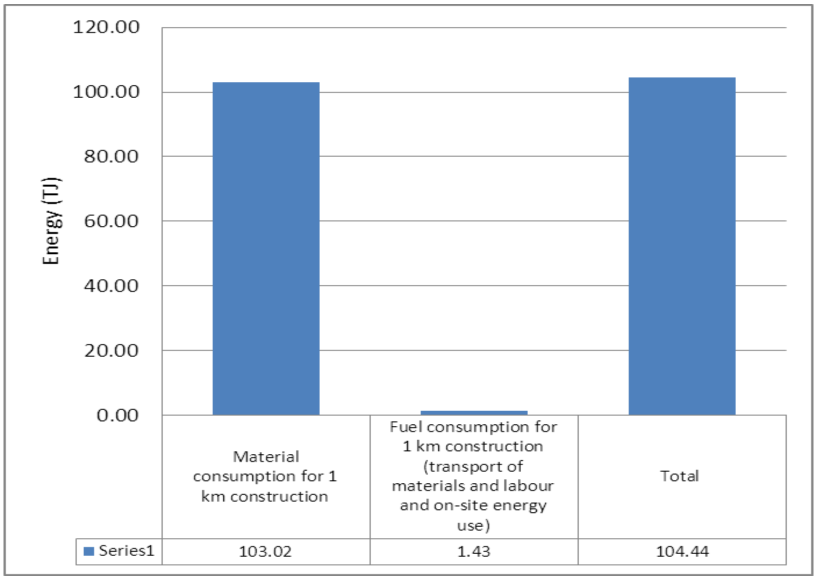
The total embodied energy and CO_2 due to energy consumption for transportation of materials and labour and on-site energy needs (for construction of 1 km Metro line) are estimated to be about **1.43 TJ and 695 tonnes,** respectively.

[79] Only the energy and CO_2 impacts of direct energy consumption for transportation are considered. Embodied energy and CO_2 of vehicles transporting materials/labour is not considered.
[80] Average loading data provided by DMRC
[81] To and fro trips of vehicles have been considered while calculating fuel consumption i.e. if a truck is making a trip to transport cement to the site, diesel consumption has been estimated for it's to and fro trip (trip from cement factory to site and back to factory).
[82] It should be noted that on-site electricity usage could not be collected due to unavailability of data with DMRC.

6.1.4 Summary construction phase (1 km Metro line) - Embodied energy and CO_2

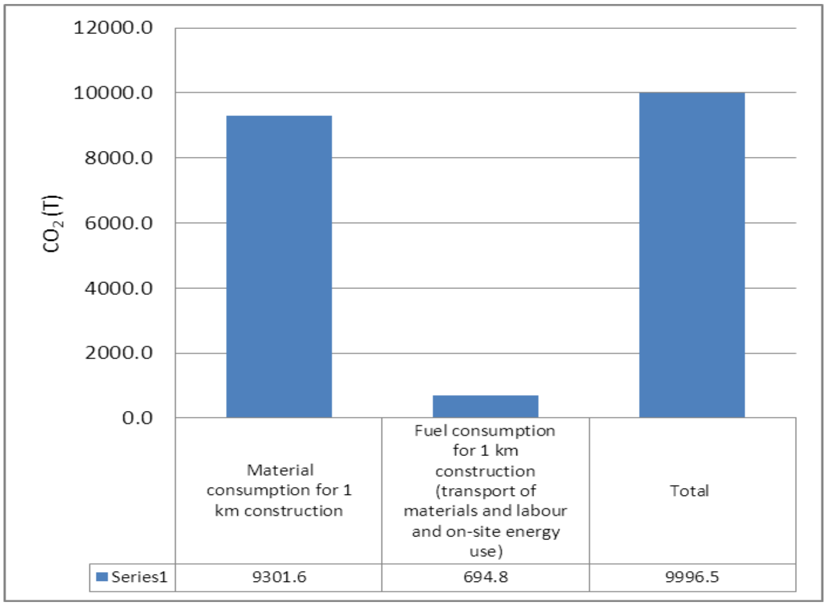
The embodied energy and CO_2 emissions estimated for construction of 1 km Metro line are summarized in figures 6.5 and 6.6. Total embodied energy and CO_2 in constructing 1 km Metro line are estimated at about **104 TJ and 9,996 tonnes**, respectively.

Figure 6.5 Metro line - Embodied energy (TJ) per km construction



Source: Analysis by TERI

Figure 6.6 Metro line - Embodied CO_2 (tonnes) per km construction



Source: Analysis by TERI

6.2 Construction of Metro station

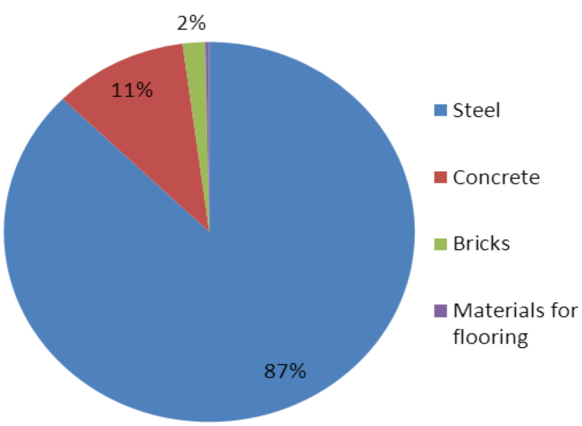
Embodied energy and CO_2 of a typical elevated Metro station (of Delhi Metro) was estimated by considering consumption of key construction materials[83]. Table 6.2 gives the quantities of key materials consumed for constructing a typical Metro station of Delhi Metro. Consumption of these materials translates into **embodied energy of about 140 TJ and embodied CO_2 equivalent to about 13,250 tonnes per Metro station**. Extensive use of steel results in very high contribution of steel (87%) to the embodied energy of a station among all materials used for station construction (figure 6.7).

Table 6.2 Key materials consumed in construction of one typical Metro station

Materials	Quantity	Unit
Concrete	5,978.0	cum
Steel reinforcement	957.0	tonnes
Structural steel	540.0	tonnes
Roof sheet - galvanized steel	1,436.5	tonnes
Steel fabrications	0.8	tonnes
Bricks	1,100.0	cum
Kota stone	95.4	cum
PVC	2.1	tonnes
Ceramic	6.9	tonnes

Source: Primary data collected by TERI from DMRC for Delhi Metro

Figure 6.7 Contribution of different materials to embodied energy of materials used for construction of a typical Metro station



Source: Analysis by TERI

[83] Only material consumption was considered in estimating embodied energy and CO_2 of Metro station.

6.3 Maintenance

During discussions with DMRC to understand the maintenance practices for metro line and the resultant material consumption, it was informed to TERI that annual maintenance practices result in very less material consumption. DMRC highlighted that this material consumption would be so small that it can be ignored. Embodied energy and CO_2 for annual maintenance of Metro line is hence not calculated. With regard to periodic maintenance/renewal, certain assumptions were made to estimate the quantum of materials consumed.

6.3.1 Periodic maintenance (30 years duration)

Within 30 years period, only rails will be replaced in a metro line as its design life is about 30 years. Per km consumption of steel (for rails) was estimated to account for this periodic renewal of rails, once in 30 years. About 264 tonnes of steel is estimated to be consumed for this purpose. This consumption translates into **8.8 TJ embodied energy and 790 tonnes embodied CO_2**.[84]

6.4 Operations

Electricity consumption data for metro rail operations was collected from DMRC's report submitted to UNFCCC[85] to get carbon credits for Phase-2 of Delhi Metro. The calculations to estimate electricity and CO_2 per PKM for Delhi Metro's operations are shown in table 6.3. Per PKM energy consumption of Delhi Metro is estimated to be about **86.4 kJ** of electricity, which translates into **19.7 g CO_2 per PKM**.

Table 6.3 Estimating Delhi Metro's operational energy consumption

	Unit	For 8 months in 2011 (Phase 2)	Remarks
No. of passengers	Passengers	386,569,310	Source: DMRC's CDM report submitted to UNFCCC
Average lead	km	14	
Passenger kms (PKM)	PKM	5,411,970,340	
Electricity consumption	kWh	129,826,000	For running trains only (Source: DMRC's CDM report)
Energy consumption per PKM	kWh/PKM	0.0240	
Energy consumption per PKM	MJ/PKM	0.0864	1kWh = 3.6 MJ
CO_2 emissions	kg/PKM	0.0197	0.82 kg CO_2/kWh for NEWNE[86] grid (Source: Central Electricity Authority, 2011)

[84] Only material consumption considered in estimating embodied energy and CO_2 of periodic maintenance/renewal.
[85] United Nations Framework Convention on Climate Change
[86] Northern, Eastern, Western, and North-Eastern grid

6.5 Embodied energy of rolling stock

Rolling stock of metro rail i.e. metro trains have embodied energy and CO_2 on account of manufacturing and maintenance processes[87]. Values from international literature have been used to understand embodied energy and CO_2 values for rolling stock. Table 6.4 gives the values for metro trains in USA.

Table 6.4 Embodied energy and CO_2 values for rolling stock - Metro trains

Metro rail	Energy (TJ)		CO_2 (T)	
	Vehicle manufacture	Vehicle maintenance (full life)	Vehicle manufacture	Vehicle maintenance (full life)
New York city metro[88]	22 (2.2 TJ/coach)	18 (1.8 TJ/coach)	1,300 (130 T/coach)	810 (81 T/coach)
Chicago metro	20	17	1,200	750

Source: Chester and Horvath (2009b)

6.6 Summary - Metro rail

Table 6.5 Life cycle embodied energy and CO_2 - Metro rail

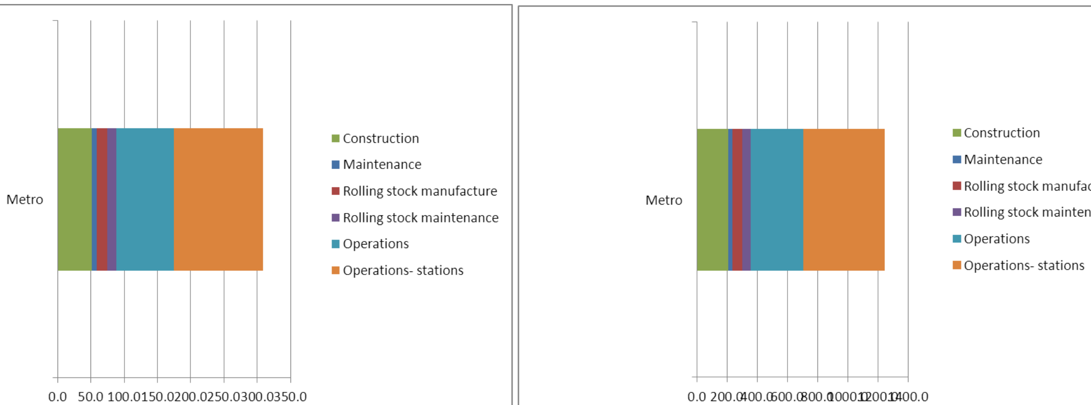
Metro rail	Phase	Embodied energy	Unit	Embodied CO_2	Unit	Remarks
Fixed infrastructure	Construction (1 km metro line and 1 station)	245.1	TJ/km	23,246.1	T/km	India-specific values, Based on TERI's analysis
	Maintenance (30years)[89]	8.8	TJ/km	792.0	T/km	
Rolling stock	Manufacture	2.2	TJ/coach	130.0	T/coach	USA-specific values, Source: Chester and Horvath (2009b)
	Maintenance (full life)	1.8	TJ/coach	81	T/coach	
	Operations	86.4	kJ/PKM	19.7	g/PKM	India-specific values, Based on TERI's analysis

[87] End-of-life embodied energy and CO_2 of rolling stock are not considered as dismantling/recycling vehicles are not widely adopted practices in Indian context.
[88] 8 to 11 cars per train
[89] Maintenance of station not included

6.7 Application of LCA results for metro rail

The LCA results derived in the previous sections have been applied to the Delhi metro rail project to estimate the full life cycle impacts of the project on a per PKM and per km basis. The assumptions, data, etc. used for the calculations are given in Annexure 1. The results are summarized in figures 6.8 and 6.9.

Figure 6.8 Delhi metro rail project (phase I and II) - Life cycle energy consumption per PKM and per km



	Metro
Construction	51.9
Maintenance	6.5
Rolling stock manufacture	16.3
Rolling stock maintenance	13.8
Operations	86.4
Operations- stations	133.4

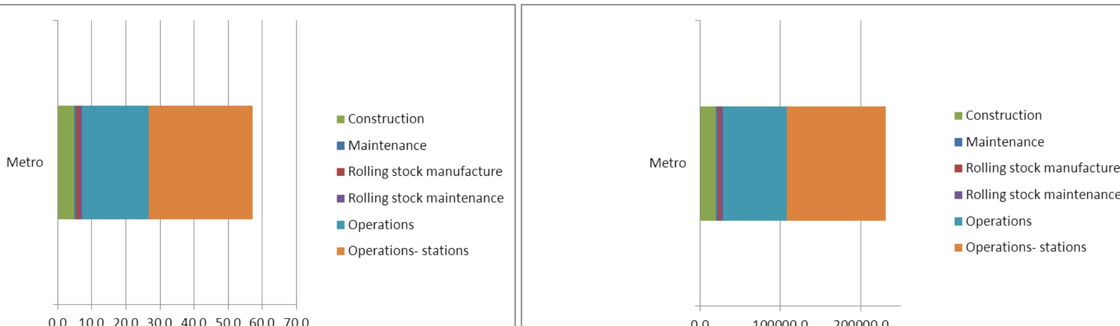
Energy - kJ/PKM

	Metro
Construction	209.7
Maintenance	26.4
Rolling stock manufacture	65.8
Rolling stock maintenance	55.9
Operations	348.9
Operations- stations	538.9

TJ/KM

Source: Analysis by TERI

Figure 6.9 Delhi metro rail project (phase I and II) - Life cycle CO_2 emissions per PKM and per km



	Metro
Construction	4.9
Maintenance	0.6
Rolling stock manufacture	1.0
Rolling stock maintenance	0.6
Operations	19.7
Operations- stations	30.4

CO2 - g/PKM

	Metro
Construction	19912.9
Maintenance	2376.0
Rolling stock manufacture	3946.7
Rolling stock maintenance	2466.7
Operations	79468.7
Operations- stations	122742.8

T/KM

Source: Analysis by TERI

Chapter 7: LCA results - City road

7.1 Construction

In order to estimate the embodied energy and CO_2 per kilometre (km) construction of an urban road, construction of roads in Delhi was studied. The data on per km road construction details was provided by the Delhi Public Works Department (PWD) based on standard practices/norms followed for construction of city roads in Delhi.

It should be noted that construction data in this case is not for a specific road construction project but an estimation of per km construction activities (material and energy consumption) based on standard practices.

Table 7.1 Details of city road construction data

Data for:	Construction of a typical road in Delhi
State:	Delhi
Length for which data was provided:	1 km
Estimated construction duration:	1 km construction in about 3 months
Design life of pavement:	15 years
Cross-section details	ROW - 35 m [Carriageway - 10.5 m (one side), Median - 1.5 m, Footpath - 2.5 m (present on both sides), Service road - 3.5 m (present on both sides)]

Source: Data provided by Delhi PWD

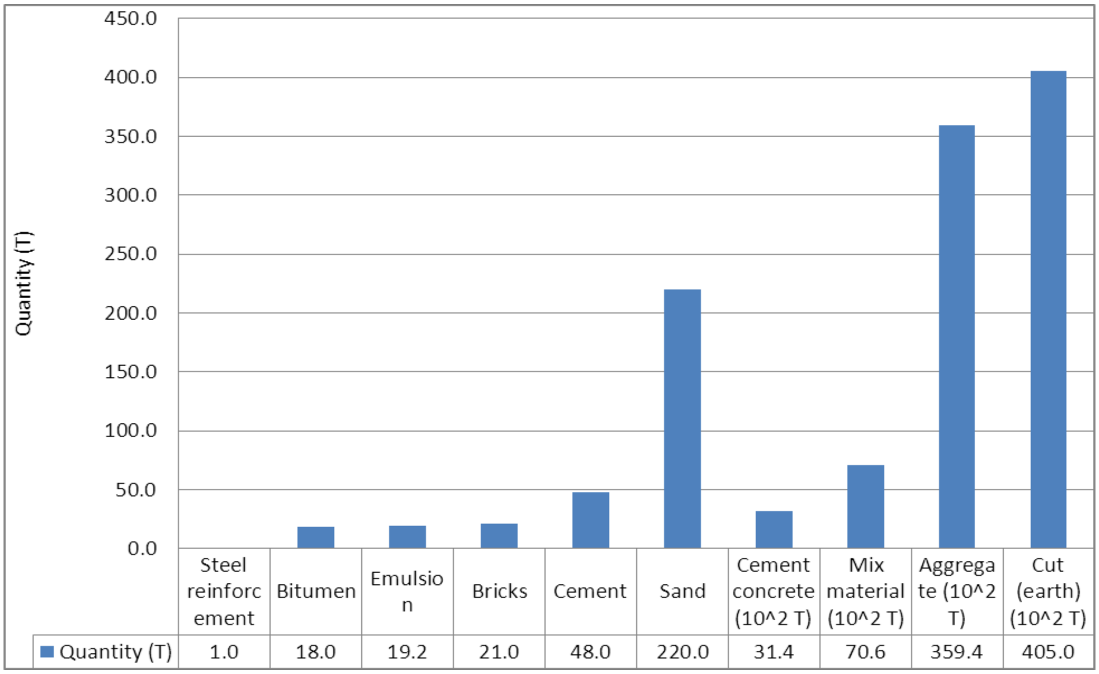
7.1.1 Consumption of materials during construction

Key materials consumed for construction of an urban road include:

- Aggregate
- Bitumen/mix material
- Bitumen emulsion
- Cement
- Steel
- Bricks
- Earth (cut and fill)

Per kilometre consumption of key materials in construction of city road is given in figure 7.1.

Figure 7.1 Consumption of key materials- 1 km city road construction



Source: Primary data collected by TERI from Delhi PWD for road construction in Delhi

Construction of 1 km city road involves significant consumption of aggregates (coarse); about 35 thousand tonnes of aggregates are consumed per km. Construction also involves substantial amount of earthwork in the form of cut and fills on the site (about 40 thousand tonnes). About 7,000 tonnes of hot mix material is used per km. Other key materials used in construction of 1 km city road include fine aggregate, cement and bricks.

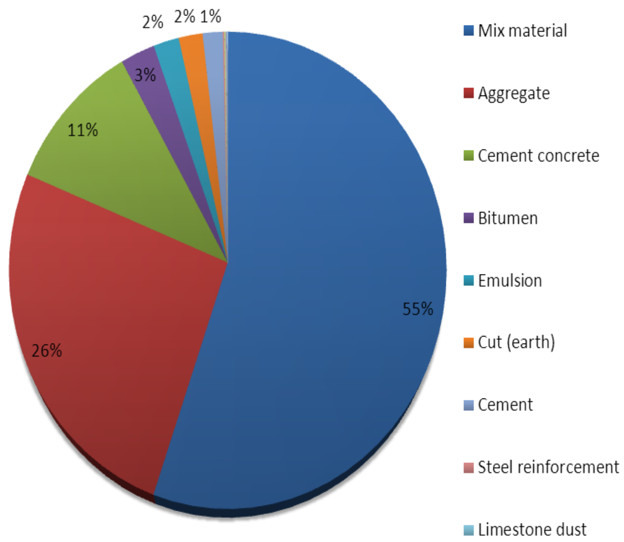
Embodied energy and CO_2 due to material consumption

Embodied energy and CO_2 due to material consumption in 1 km city road construction was estimated by using India-specific embodied energy and CO_2 coefficients for materials.[90] The embodied energy and CO_2 of materials used per km city road construction is estimated to be about **31 TJ and 2,160 tonnes**, respectively.

Hot mix material has maximum contribution (55%) to the embodied energy of per km materials used (figure 7.2). Aggregate and cement concrete consumption contributes 26% and 11% embodied energy, respectively. In case of embodied CO_2 per km materials used, hot mix material has the maximum contribution of about 46%, followed by aggregates (36%) and cement concrete (14%) (figure 7.3).

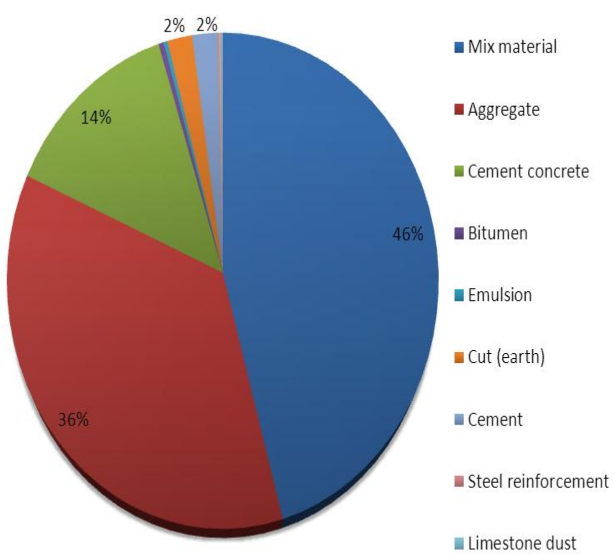
[90] In case, India specific embodied energy coefficients were not available for some materials, the same were derived from international literature.

Figure 7.2 Contribution of different materials to embodied energy of materials used per km city road construction



Source: Analysis by TERI

Figure 7.3 Contribution of different materials to embodied CO_2 of materials used per km city road construction

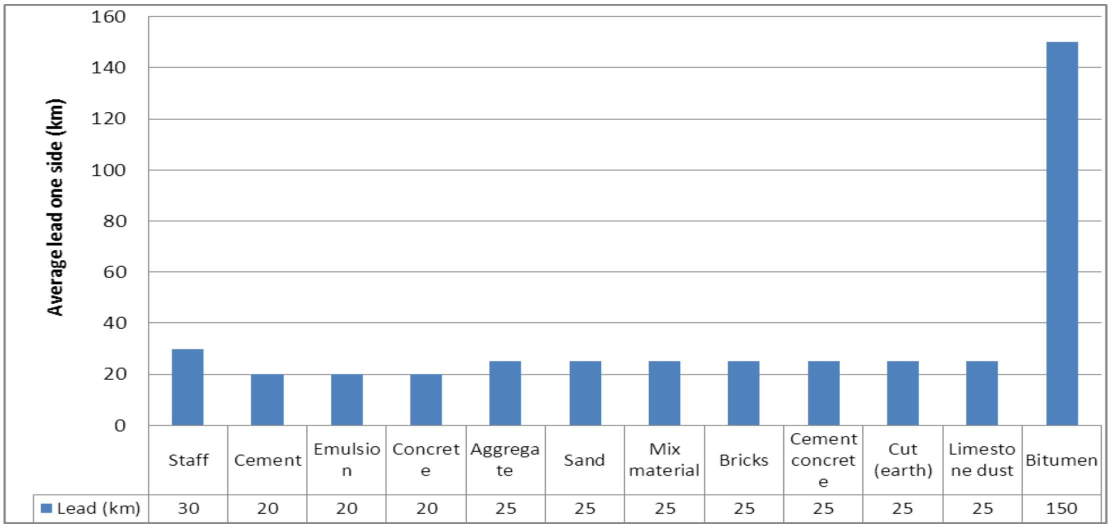


Source: Analysis by TERI

7.1.2 Energy consumption during construction - Transportation of materials and labour and on-site energy consumption

The average lead for material and labour transportation for construction of roads in Delhi ranges from 20 km to 150 km (figure 7.4). Road-based modes like dumpers and trucks are used for transportation. The number of trips for transportation were estimated based on quantities transported (figure 7.1) and average loading[91] on different modes and then used to estimate the diesel consumption.[92]

Figure 7.4 Average lead for materials and labour transportation



Source: Primary data collected by TERI for road construction in Delhi

In addition to energy consumption for transportation of materials, energy is also needed to carry out on-site construction works that involve running of machinery, equipments and vehicles. Data on on-site energy consumption in the form of electricity and diesel was collected from Delhi PWD.

Embodied energy and CO_2 due to energy consumption during construction

India-specific embodied energy coefficients[93] and CO_2 emission factors[94] were used[95] to estimate the total embodied energy and CO_2 due to energy consumption for transportation of materials and labour and on-site energy needs (for construction of 1 km city road). This energy consumption translates into **0.6 TJ embodied energy per km and 275 tonnes embodied CO_2 per km** respectively.

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[91] Average loading data was taken from Delhi PWD.

[92] To and fro trips of vehicles have been considered while calculating fuel consumption i.e. if a truck is making a trip to transport cement to the site, diesel consumption has been estimated for it's to and fro trip (trip from cement factory to site and back to factory).

[93] Energy required to produce 1 unit of fuel.

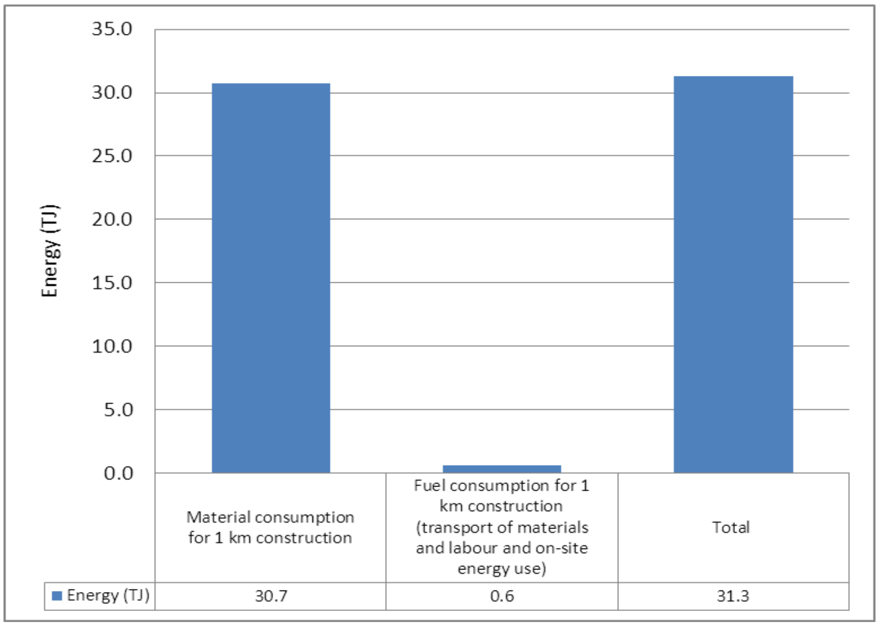
[94] CO_2 emission factors used for fuels include embodied CO_2 in fuels i.e. CO_2 emitted to produce 1 unit of fuel and CO_2 at tail-pipe due to combustion of fuel.

[95] In case, India specific embodied energy coefficients were not available, the same were derived from international literature.

7.1.3 Summary construction phase - Embodied energy and CO_2

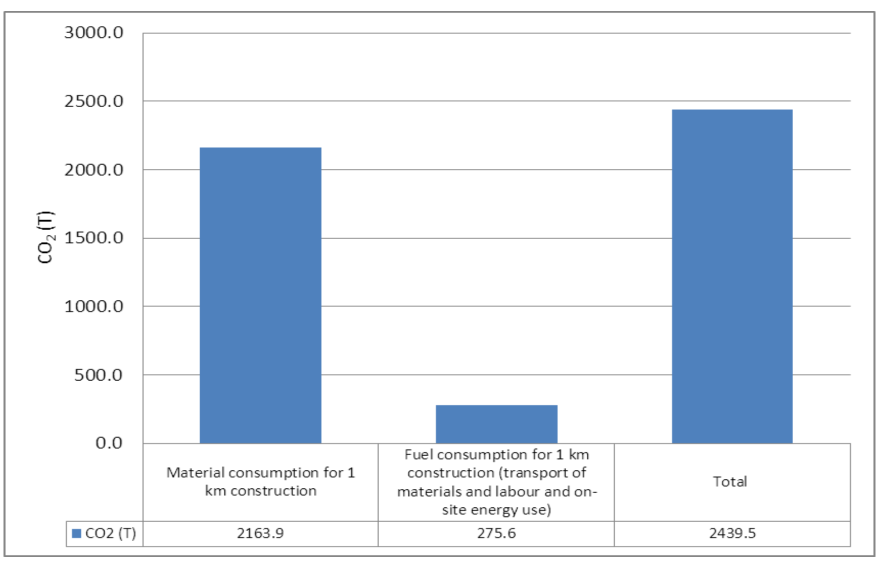
The embodied energy and CO_2 emissions estimated for construction of 1 km city road are summarized in figures 7.5 and 7.6. Total embodied energy and CO_2 in constructing 1 km city road are estimated at about **31 TJ and 2,440 tonnes**, respectively.

Figure 7.5 City road - Embodied energy (TJ) per km construction



Source: Analysis by TERI

Figure 7.6 City road - Embodied CO_2 (tonnes) per km construction



Source: Analysis by TERI

7.2 Maintenance

Maintenance practices for a road in Delhi were studied in order to estimate the embodied energy and CO_2 per kilometre (km) maintenance. The data on per km road maintenance details was provided by the Delhi Public Works Department (PWD) based on standard practices/norms followed for maintenance of city roads in Delhi.

It should be noted that maintenance data in this case is not for a specific road construction project but an estimation of per km maintenance activities based on standard practices.

Table 7.2 Details of the city road maintenance data

Data for:	Maintenance of a typical road in Delhi
State:	Delhi
Length for which data was provided:	1 km
Periodic maintenance cycle:	Bituminous overlays after every 5 years
Design life of pavement:	15 years
Cross-section details	ROW - 35 m [Carriageway - 10.5 m (one side), Median - 1.5 m, Footpath - 2.5 m (present on both sides), Service road - 3.5 m (present on both sides)]

Source: Data provided by Delhi PWD

7.2.1 Annual routine maintenance

Data on material consumption for annual routine maintenance activities provided by Delhi PWD (table 7.3) was used to estimate per km embodied energy and CO_2 for annual maintenance activities. Embodied energy and CO_2 values are estimated as **0.6 TJ and 41.5 tonnes,** respectively.[96]

Table 7.3 Annual routine maintenance of city road - Material consumption per km

Materials	Consumption (in tonnes) per km maintenance (annual)
Aggregate	37.5
Cement	1.0

[96] Only material consumption is considered for estimating the embodied energy and CO_2 of maintenance activities (annual and periodic).

Materials	Consumption (in tonnes) per km maintenance (annual)
Sand	22.0
Bitumen emulsion	1.0
Mix material	120.0
Cement concrete	192.0
Paint	1.32

Source: Data provided by Delhi PWD for annual road maintenance in Delhi

7.2.2 Periodic maintenance (30 years duration)

Material consumption for periodic maintenance was estimated based on data provided by Delhi PWD; table 7.4 gives the per km material consumption for one periodic renewal.[97]

Table 7.4 Periodic renewal (once in 5 years) of city road (bituminous surface) - Material consumption per km

Materials	Consumption (in tonnes) per km periodic maintenance (5-yearly)
Aggregate	25.0
Sand	770.0
Bitumen	18.0
Mix material	2436.0
Cement concrete	1944.0

Source: Data provided by Delhi PWD for periodic road maintenance in Delhi

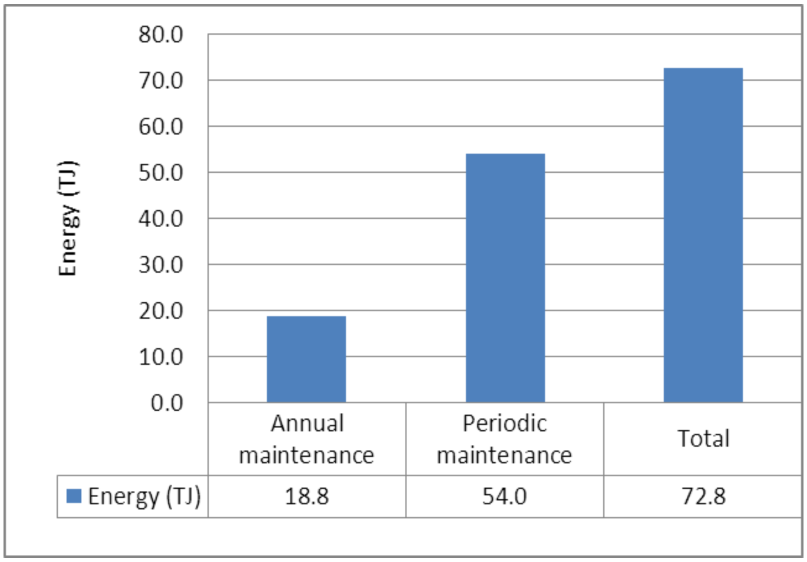
Consumption of materials for periodic renewal in 30 years period translates into **54 TJ embodied energy and 3,350 tonnes embodied CO_2**.

[97] It should be noted that the maintenance activities considered do not include the consumption of materials for strengthening of the road.

7.2.3 Summary maintenance phase - Embodied energy and CO_2

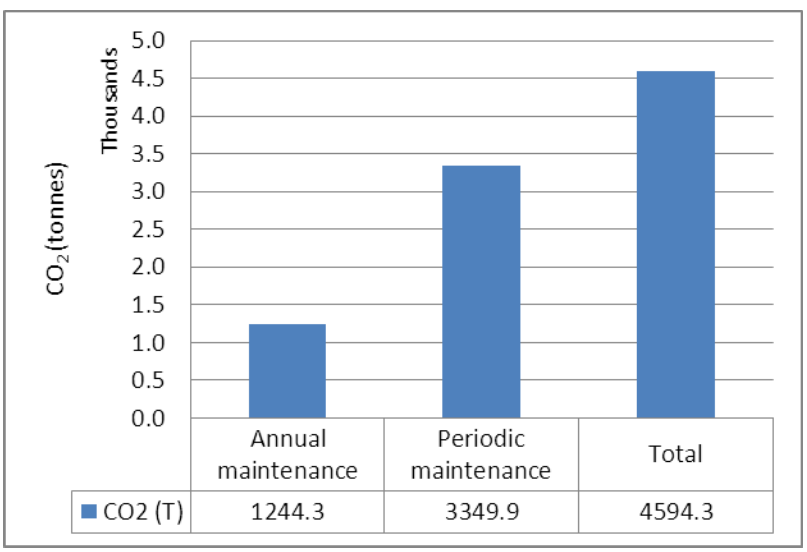
Annual routine maintenance and periodic maintenance/renewal for a 30 year period translates into **embodied energy of about 73 TJ and embodied CO_2 of about 4,595 tonnes** (figures 7.7 and 7.8).

Figure 7.7 Maintenance of city road for 30 years - Embodied energy (TJ) per km



Source: Analysis by TERI

Figure 7.8 Maintenance of city road for 30 years - Embodied CO_2 (tonnes) per km



Source: Analysis by TERI

7.3 Operations

Operational energy consumption of cars (petrol, diesel, CNG car) and two-wheelers was estimated by using secondary data (average fuel efficiency and occupancy) from Society of Indian Automobile Manufacturers (SIAM[98]), Bureau of Energy Efficiency (BEE), and TERI publications. Table 7.5 shows the estimations for energy consumption per PKM and CO_2 per PKM derived for these modes.

Table 7.5 Estimating energy consumption per PKM and CO_2 per PKM of cars and two-wheelers

	Unit	Petrol car	Diesel car	CNG car	Two wheeler	Remarks
Fuel efficiency	l/100km	8.5	9.5	8.0	1.7	Source: TERI, ARAI, BEE
Fuel consumed per km	l or cum	0.085	0.095	0.080	0.017	
Occupancy	Passengers	1.5	1.5	1.5	1.2	Source: TERI
PKM (1 km)	PKM	1.5	1.5	1.5	1.2	
Fuel consumed per PKM	l/PKM or cum/PKM	0.0567	0.0633	0.0533	0.0142	
Fuel consumed per PKM	MJ/PKM	1.8700	2.3433	2.2933	0.4675	Calorific values: Petrol - 33MJ/l; Diesel - 37MJ/l; CNG - 43MJ/cum
Tail-pipe CO_2 emissions	kg/PKM	0.1296	0.1736	0.1287	0.0324	CO_2 emission factor: Petrol - 0.0693 kg/MJ; Diesel - 0.0741 kg/MJ; CNG - 0.0561 kg/MJ
CO_2 emissions on account of fuel production	kg/PKM	0.0165	0.0150	0.0094	0.0041	CO_2 emission factor for fuel production: Petrol - 0.0088 kg/MJ; Diesel - 0.0064 kg/MJ; CNG - 0.0041 kg/MJ
Total CO_2 emissions	kg/PKM	0.1460	0.1886	0.1381	0.0365	

Source: Analysis by TERI

[98] SIAM's Fuel Efficiency Brochure

The energy consumption and CO_2 emissions due to urban bus operations were also estimated by following the method discussed in section 3.3 of Chapter 3. The results are given in table 7.6.

Table 7.6 Energy consumption and CO_2 emissions per PKM for urban bus operations

	Energy consumption	CO_2 emissions
	kJ/PKM	g/PKM
Urban bus (diesel) - Chennai	134.2	10.8
Urban bus (diesel) - BEST	270.2	21.8
Urban bus (diesel) - Bangalore	213.9	17.2

Source: Analysis by TERI

7.4 Embodied energy of rolling stock

As described earlier, international literature was reviewed to understand embodied energy and CO_2 values for rolling stock. Table 7.7 gives the values for cars in USA.

Table 7.7 Embodied energy and CO_2 values (vehicle manufacture and maintenance) for rolling stock - Cars

Cars	Energy (TJ)		CO2 (T)	
	Vehicle manufacture	Vehicle maintenance (full life)	Vehicle manufacture	Vehicle maintenance (full life)
Petrol car (sedan)	0.10	0.04	8.50	3.30
Diesel car (sedan)	0.12	0.04	9.80	3.30

Source: Chester and Horvath (2009b)

7.5 Summary - City road

Table 7.8 Life cycle embodied energy and CO_2 - City road

City road	Phase	Embodied energy	Unit	Embodied CO_2	Unit	Remarks
Fixed infrastructure	Construction	31.3	TJ/km	2439.5	T/km	India-specific values, Based on TERI's analysis
	Maintenance (30years)	72.8	TJ/km	4594.3	T/km	
Rolling stock	Manufacture	0.10 0.12	TJ/car (petrol) TJ/car (diesel)	8.50 9.80	T/bus (petrol) T/car (diesel)	USA-specific values, Source: Chester and Horvath (2009b)
	Maintenance (full life)	0.04 0.04	TJ/car (petrol) TJ/car (diesel)	3.30 3.30	T/bus (petrol) T/car (diesel)	
Rolling stock	Operations	1870.0 2343.3 2293.3 467.5	kJ/PKM (petrol car) kJ/PKM (diesel car) kJ/PKM (CNG car) kJ/PKM (two-wheeler)	146.0 188.6 138.1 36.5	g/PKM (petrol car) g/PKM (diesel car) g/PKM (CNG car) g/PKM (two-wheeler)	India-specific values, Based on TERI's analysis

Chapter 8: Conclusions

The study has sought to establish a comprehensive and robust methodology to estimate the life cycle energy and CO_2 emissions impacts of transport modes. The methodology can help take into account the energy efficiency and CO_2 impacts before arriving at investment decisions related to choice of transport modes. This becomes particularly important in the context of on-going concerns regarding energy security and climate change impacts of transport sector.

The application of the LCA methodology in this study indicates that LCA is doable for transport projects. This is indeed the biggest contribution of the study. The study has contributed in shifting focus to life stages of transport projects (i.e. construction, maintenance, manufacture of rolling stock, etc.) that are usually ignored while assessing environmental impacts. The study is useful in two ways- it can help in choice of modes and in improvement within the modes.

The life cycle analysis carried out for typical transport projects using the proposed LCA methodology indicates that there are significant energy and CO_2 related impacts of transport systems throughout their life. Currently, the decision-making processes consider the energy and CO_2 impacts due to movement of rolling stock only, which gives an incomplete assessment of impacts. In addition to impacts due to rolling stock movement, there are significant energy and CO_2 impacts due to construction and maintenance of transport infrastructure. Construction and maintenance of transport infrastructure involves consumption of materials and fuels, some of which are highly energy and carbon intensive. LCA results indicate significant contribution of such materials and fuels to life cycle energy and CO_2 impacts of transport modes. Using alternative materials and fuels that are less energy and carbon intensive and are locally available can help reduce these impacts. Research studies on alternative materials and fuels should be conducted in order to identify energy efficient and low-carbon substitutes to conventional materials and fuels.

The results of this study show that an understanding of the full-life cycle energy and CO_2 impacts of transport modes can help choose modes or suggest inter-modal shift towards modes that are least energy and carbon intensive throughout their lives. In addition to choice of mode or promoting modal shift towards more 'green' modes, life cycle analysis can also help in intra-mode greening, as it helps understand the share of various components that contribute to energy consumption and CO_2 emissions, hence helping in identifying the appropriate mitigation measures.

Also, understanding the extent of impacts and reasons for the same will help identify the mitigation measures to reduce the impacts. Some possible areas where energy reduction can be achieved during the life of a transportation system are:

- Reducing energy and CO_2 intensity of conventional materials used,
- Using alternative materials that are comparatively less energy and CO_2 intensive,
- Using locally available materials,
- Using energy efficient processes and machinery during construction and maintenance,

- Optimizing resource utilization during construction and maintenance, especially for transportation of materials (using locally available materials, reducing idling, using rail for bulk transport of materials, etc.),
- Promoting inter-modal shift (towards more energy efficient modes),
- Improving efficiency of rolling stock, and
- Reducing energy and material intensity during manufacturing and maintenance of rolling stock.

The study findings also indicate that if life of projects is enhanced, then the energy and CO_2 impacts due to re-construction can be reduced/deferred, especially in the case of road-based projects that tend to have shorter life. Life of the projects can be enhanced by continued maintenance. Maintenance of constructed assets should hence be given due importance; it will help reduce both monetary and environmental costs on a life cycle basis.

Traditional environmental impact asessment exercises carried out to support decision-making in transport sector do not consider the full life cycle energy and CO_2 impacts of transport modes. It is important that decisions related to choice of transport modes consider the life cycle impacts in terms of energy and CO_2 emissions in addition to other financial, technical, and environmental criteria used today.

In addition to financial and technical feasibility and environmental impact assessment exercises carried out at project selection/development stage, LCA estimating energy and CO_2 impacts should also be carried out. As stated earlier, this study has sought to establish a robust methodology to estimate the life cycle impacts. Further work is necessary to fine-tune the methodology and adapt it for use on a continuous basis for taking informed investment decisions. The successful use of the methodology will depend on the data available and data availability is a challenge in India. Database should be constructed to support the LCA.

Hence, to be able to use LCA in transport sector decision making, research and supporting database creation should be encouraged and supported by the government.

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Annexure 1: Application of LCA results for BRTS and MRTS to estimate life cycle energy and CO_2 impacts of Ahmedabad BRT and Delhi metro rail

The LCA results derived for BRTS and MRTS have been applied to the Ahmedabad BRT and Delhi metro rail projects to estimate the full life cycle energy and CO_2 impacts of these projects. As is the practice in many international papers, the impacts have been derived both for 'per km' and 'per PKM' units. The results have been presented in Chapters 5 and 6. The assumptions, data, etc. used for the calculations are discussed in this annexure.

Ahmedabad BRTS

- Total life of the fixed infrastructure i.e. the bus lanes and bus stops assumed to be 30 years
- Total life of the rolling stock i.e. the buses assumed to be 15 years, which implies that in a 30 year period, the rolling stock is procured twice
- Calculations have been done for the entire planned BRT corridor expected to be operational from March 2014 i.e. corridor length of about 129 kms having 249 bus stops
- As per the data provided by CEPT, once the BRTS is fully functional, 737 AC buses will be plying per day
- Passenger km (PKM) is estimated based on the design capacity of the Ahmedabad BRTS system i.e. 10.32 lakh passengers per day

Delhi Metro

- Total life of the fixed infrastructure i.e. the viaduct and stations assumed to be 100 years
- Total life of the rolling stock i.e. the trains assumed to be 30 years, which implies that in a 100 year period, the rolling stock is procured thrice
- Calculations have been done for the phase 1 and 2 of Delhi metro i.e. track length of 189.7 km having 142 stations
- As per the data collected from the annual reports of DMRC, about 208 trains ply per day on phase 1 and phase 2 network
- Passenger km (PKM) is estimated based on the current average ridership of the phase 1 and 2 i.e. 15 lakh passengers per day

About Sustainable Habitat Division, TERI

The Sustainable Habitat Division at TERI is comprised of three research areas: the Center for Research on Sustainable Building Sciences (CRSBS), the Center for Research on Sustainable Urban Development and Transport Systems (CRSUDTS), and the Association for Development and Research on Sustainable Habitats (ADaRSH).

CRSBS is dedicated to all aspects of energy and resource efficiency in buildings and has been offering environmental design solutions for habitat and buildings of various complexities and functions for nearly two decades. It consists of architects, planners, engineers, and environmental specialists who specialize in urban and rural planning, low energy architecture and electromechanical systems, water and waste management and renewable energy systems. A regional center in Bangalore has been set up to facilitate development and mainstreaming of sustainable buildings, improve performance levels of existing buildings, and raise awareness on sustainable buildings in Southern India.

CRSUDTS works extensively on various urban issues with an aim to promote sustainable urban development. It was established in 1999 in response to the growing urban demands, particularly in the urban infrastructure sectors. CRSUDTS is involved in research related to urban transport and sustainability issues. It's activities range from carrying out energy-environment related analysis, giving inputs to policy and planning, improving urban service provision and governance, carrying out sustainability assessments, exploring climate change implications and carrying out capacity building for various stakeholders, all in the context of the transport and urban development sectors.

ADaRSH has been setup as an independent entity to promote GRIHA and its associated activities.

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