81572

Transport Research Support

COMPARATIVE ANALYSIS OF ENERGY CONSUMPTION AND GREENHOUSE GAS EMISSIONS BY ALTERNATIVE URBAN TRANSPORT SYSTEMS

RUI WANG

DFID Department for International Development

1818 H Street NW
Washington DC 20433
Telephone: 202-473-1000
Internet: www.worldbank.org
E-mail: feedback@worldbank.org

COMPARATIVE ANALYSIS OF ENERGY CONSUMPTION AND GREENHOUSE GAS EMISSIONS BY ALTERNATIVE URBAN TRANSPORT SYSTEMS

The Transport Research Support program is a joint World Bank/ DFID initiative focusing on emerging issues in the transport sector. Its goal is to generate knowledge in high priority areas of the transport sector and to disseminate to practitioners and decision-makers in developing countries.

CONTENTS

LIST OF TABLES

LIST OF FIGURES

ACKNOWLEDGEMENTS

The "Comparative Analysis of Energy Consumption and Greenhouse Gas Emissions by Alternative Urban Transport Systems" has been prepared for the World Bank Transport Anchor group (TWITR) in Washington which administers and manages the Transport Research Support Program, TRSP, a financing of **DFID**, the Department for International Development of the United Kingdom Government.

Supervised and supported by the World Bank team, Dr. Rui Wang of the University of California, Los Angeles, was the lead consultant of this project. Domestic data collection work was assisted by Dr. Xinmiao Yang's team from Tsinghua University and Mr. Zhenyu Li's team from the China Academy of Transportation Sciences.

EXECUTIVE SUMMARY

The goal of this project is to collect data and develop methodologies and a spreadsheet tool for comparing lifecycle energy consumption and greenhouse gas (GHG) emissions of alternative urban transport projects/systems (i.e., single or combinations of urban transport modes) serving a typical Chinese city, with an application to Kunming's Subway Line No. 3. This project is commissioned by the World Bank under its "China Urban Transport, Energy Efficiency and Climate Change Program," which aims to mainstream the climate consideration in urban transport planning and investments.

Supervised and supported by the World Bank team, Dr. Rui Wang of the University of California, Los Angeles, was the lead consultant of this project. Domestic data collection work was assisted by Dr. Xinmiao Yang's team from Tsinghua University and Mr. Zhenyu Li's team from the China Academy of Transportation Sciences.

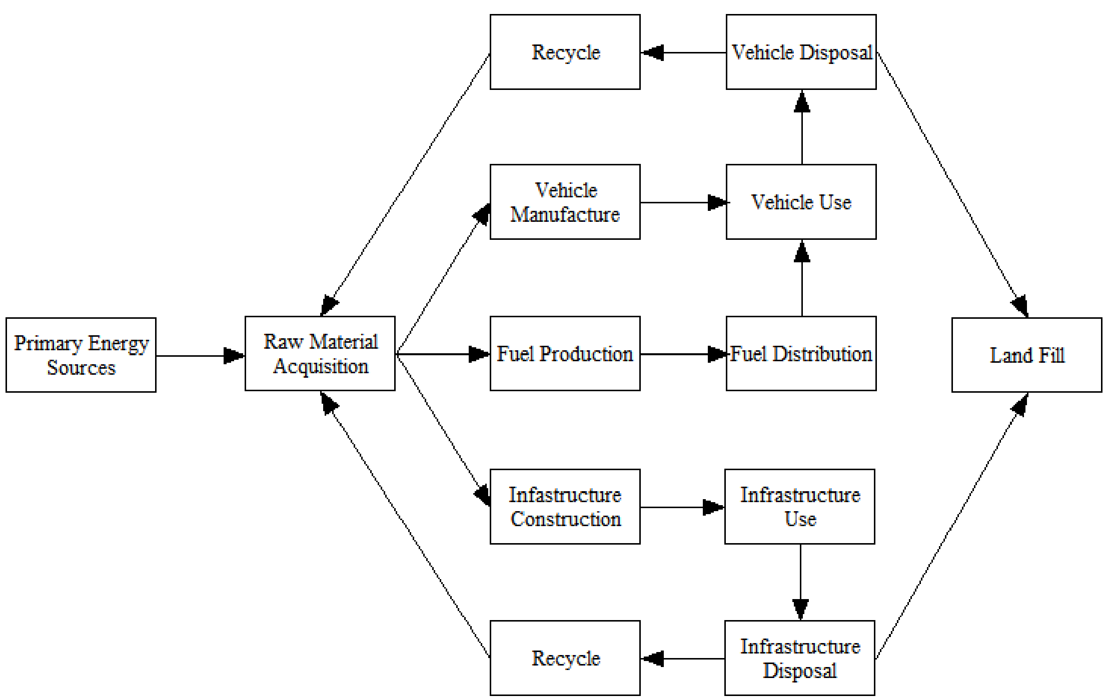
This report provides the intellectual context of the project, introduces the conceptual framework and the spreadsheet tool, and comments on preliminary findings from running the spreadsheet tool using data from Kunming.

1 Intellectual Context

1.1 Concept of lifecycle analysis

Lifecycle analysis (LCA) aims to systematically measure resource consumption and environmental releases that are associated with products, processes and services. Typical lifecycle stages include extracting and processing raw materials, manufacturing, transportation and distribution, use/reuse, and recycling and waste management. LCA is particularly suitable for measuring GHG emission impact because GHGs, unlike conventional air pollutants, have the same climate effects regardless of where they are emitted. For transport systems, a typical energy/GHG LCA can be understood through measuring energy/GHG impacts of each of the modules in the lifecycle of a transport system as shown in Figure 1.

Figure 1: Transport energy/GHG LCA modules



1.2 Development of knowledge and tools

Transport environmental evaluation tools, such as MOBILE6 and the more recent MOVES, both mobile emission estimation tools developed by the U.S. government, have long been primarily concerned with conventional and GHG emissions from tailpipe. With the growing interest in alternative fuels and vehicle technologies, research integrating full fuel cycle in evaluating alternative fuels or fuel-vehicle technology systems (e.g. Weiss et al 2000, Hackney and de Neufville 2001, Delucchi 2003, Ogden et al 2004) emerged in the recent past. Important evaluation tools such as the Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET) models have been developed to conduct LCA.[1] However, most of these studies and tools[2] focus on light-duty vehicles only, instead of comparing alternative transport modes or systems.

Among the small number of LCA studies/tools that compare alternative transport modes, emissions from infrastructure are often ignored (e.g., Karman 2006, Cherry et al 2009) or very crudely represented (Delucchi 2003 and 2005). If only fuel or fuel-engine lifecycles are analyzed, an alternative evaluation will bias toward capital- or infrastructure-intensive modes. A notable exception is the work by Chester (2008) and Chester and Horvath (2009), which establishes a lifecycle energy/GHG inventory of major passenger modes in the U.S. It finds that in addition to petroleum refining and vehicle manufacturing, infrastructure construction is a significant contributor to lifecycle energy consumption and GHG emissions of automobile, bus and rail.

1.3 Methodology of lifecycle analysis

There are primarily two ways to conduct LCA: one based on production/service process and one based on economic input-output (IO) data. Process-based LCA aggregates emissions from each process component of the production/service in question. It is specific and detailed (see, e.g., Santero and Horvath, 2009), while generally incomplete due to the inevitable problem of system cutoffs. For example, the second-order effects from producing the machines that manufacture a vehicle are often excluded in a transport LCA. IO-based LCA is based on available economic IO data, which depicts inter-industry relations of a national or regional economy (Leontief, 1970). In theory, it is more complete in system boundaries because economic IO data represent the aggregation of first- and higher-orders of inter-industry flows. However, IO-based LCA is only feasible when the process being evaluated reasonably matches an economic sector in the economic IO table. As most IO data report flows measured by economic value, one would also need appropriate price data to reconstruct material flows. The economic, energy, and resource interactions between sectors in the model are based on sector-wide averages. IO data can also be considered as outdated in certain situations (e.g., in economies with rapid changes in technology, productivity or real

[1] The GREET models provide emissions factor data that are used by many of the other LCA tools.

[2] For more information on detailed process-based evaluation tools, visit EPA's Transportation and Climate: Tools, Analysis and Publications website.

price) because it often takes years to produce an economy-wide IO table. A good summary of IO-based LCA is EIO-LCA (2009).

In transport LCAs, both methods have been used depending on analysis scope, level of detail, and data availability. In fact, hybrid LCA has long been regarded as a solution to take the advantages of both methods. It uses IO-based LCA when lifecycle components match sectors in existing IO table (typically lower-level/simple processes such as production of steel) and process-based LCA otherwise (typically higher-level/specific processes such as the operation of a train system), capturing lifecycle effects as completely as possible. For example, Delucchi (2003, 2005)'s Lifecycle Emissions Model (LEM) (and the more recently developed GHGenious, a tool based on LEM) and Chester (2008)'s inventory both employ the hybrid LCA strategy to estimate lifecycle emissions of various processes. Of course, it is more difficult to apply the hybrid LCA in many countries other than the U.S. because few have IO data as detailed as the U.S. For instance, the U.S. 2002 national IO table includes 428 sectors, while only 122 sectors exist in China's recent 2002 IO table. The much smaller number of sectors means there are much fewer reasonable matches between lifecycle processes and the highly aggregated industries in the IO table.

LCAs are not only data intensive, but also methodologically so complicated that it is often difficult to systematically compare their quality. Existing LCAs of transport systems involve a large amount of data and numerous assumptions, approximations, and explicit/implicit boundary cutoffs. It is not surprising to see significant differences in findings across studies/inventories within the same country, such as the relative sizes of capital (upstream) emissions compared to operational emissions. To link methodologies to differences in final results is very difficult, meaning it is often impossible to argue which method/dataset/result is superior to others. For example, there has been no empirical comparison between process-based and IO-based analyses, making it impossible to answer questions such as how big the differences are, which method performs better and under what conditions, etc. On the other hand, LCAs often involve processes that are non-uniform across time and space. To produce a reliable LCA usually requires a locally estimated data inventory. For this reason, not only the absolute estimates, but also the relative importance of each lifecycle component is generally non-transferrable across location and time. In sum, the "optimal" methodology to conduct LCA in a specific situation is affected by data availability and the level of aggregation.

1.4 Transport LCA vs. other GHG accounting protocols

It is important to note that the LCA tools are different from the group of registry-oriented inventory tools, such as World Resources Institute's Greenhouse Gas Protocol, the Climate Registry's General Reporting Protocol, California Climate Action Registry's General Reporting Protocol, International Council for Local Environmental Initiatives (ICLEI)'s Local Government Operation Protocol, U.S. EPA climate leaders' cross sector guidance, Environmental Defense Fund/NAFA Fleet Management Association's fleet greenhouse gas emissions calculator, and the IFC Carbon Emissions Estimation Tool (CEET). Such inventory tools are most suitable for standardized voluntary reporting, carbon trading, and regulatory compliance. These tools generally follow what has become a standard "three-scope" division of emissions: direct emissions controlled by the agency such as mobile combustion and refrigerant leaks (Scope 1), indirect emissions that occur outside the agency such as purchased electricity (Scope 2), and "optional" emissions such as the indirect upstream and downstream lifecycle emission (Scope 3). For example, the CEET is a multi-sector carbon accounting tool, accounting for operational emissions (including direct emissions from purchased energy) and optionally emissions from construction. It uses the process-based carbon accounting method with decomposed standardized process/product emissions. Such data and method can be acceptable for cross-country/region emission estimation of certain industries/projects (for which data are available and technologies are similar across country/region). CEET is not a lifecycle carbon accounting tool because of its optional inclusion of construction phase and unclear system cutoffs. Within its own scope of accounting, CEET is difficult to be used to evaluate multimodal urban transport systems for two reasons. First, it is not detailed enough to account for the different production processes of transport systems. Second, it cannot work directly with standard outputs of travel demand models.

2 A MODEL FOR LIFECYCLE ANALYSIS OF URBAN TRANSPORT SYSTEMS IN CHINA

2.1 CONCEPTUAL FRAMEWORK

In order to compare alternative urban transport systems' lifecycle energy and GHG performance, it is necessary to develop a model flexible enough to calculate lifecycle energy and GHG impacts under alternative scenarios of urban transport system development, based on common assumptions of technologies and practices in Chinese cities.

FIGURE 2: CONCEPTUAL FRAMEWORK

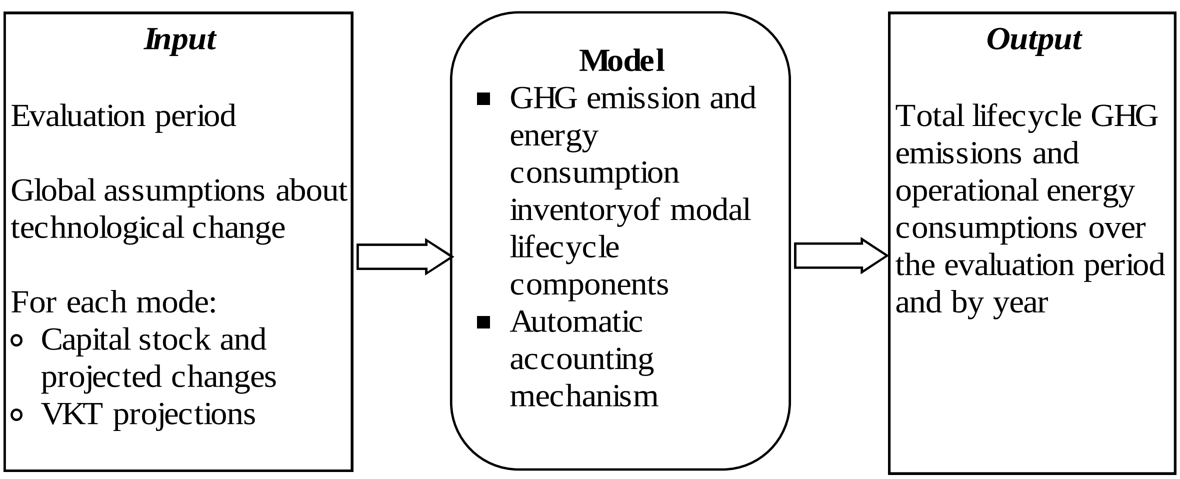
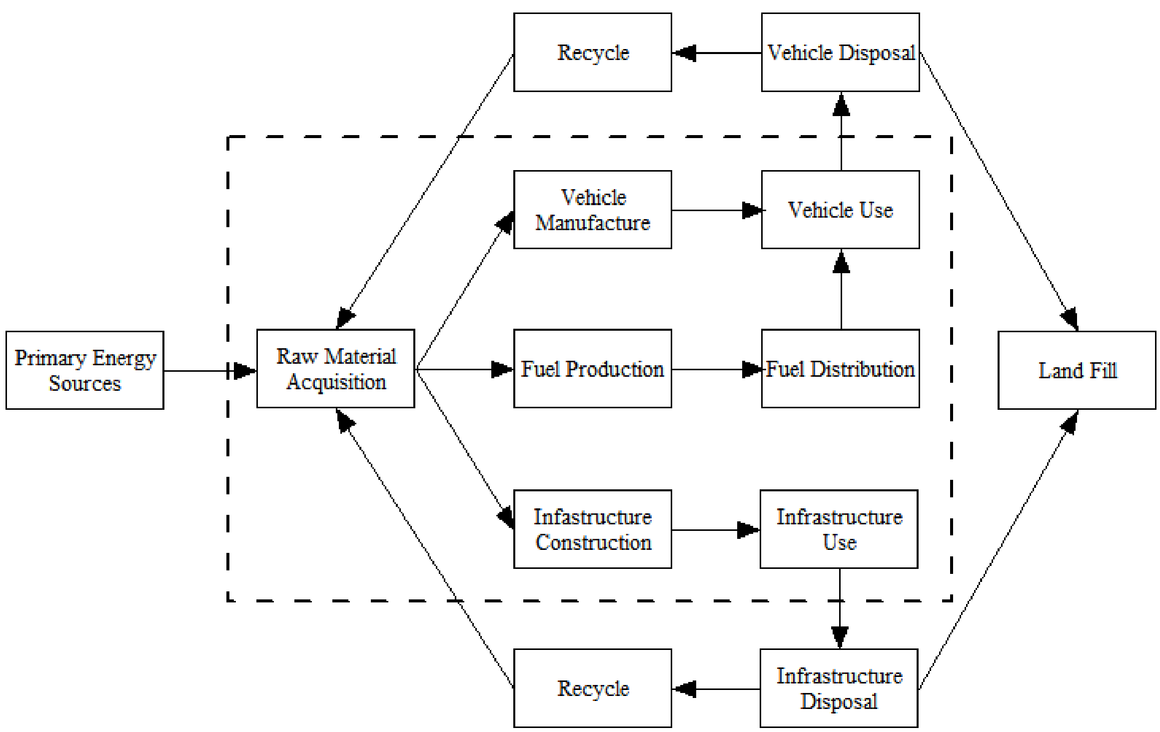


Figure 2 above shows the framework for estimating lifecycle emissions of energy use and GHG emissions from a given urban transportation system in China. The framework explains major model components, user input data and model output.

The model takes three parts of input, period of evaluation, global assumptions on technological change (fuel efficiency and power carbon intensity), and mode-specific information on capital and operation (i.e., output of travel demand models) of the urban transport system in question. As output, the model generates energy consumption and GHG emissions of the proposed urban transport system by year during the study period.

The model includes a lifecycle data inventory estimated for Chinese cities and a programmed calculation mechanism. For the inventory, lifecycle energy and GHG impacts are separately estimated by decomposing a urban transport system into units of standardized capitals (e.g., a standard diesel bus, per km elevated rail right-of-way, etc.) and service delivered (e.g., vehicle-km). The lifecycle components considered by the model include manufacturing (from extraction of raw material), operation and maintenance of vehicle, construction (from extraction of raw material), operation and maintenance of infrastructure, and production and distribution of fuel/power. The model builds the first comprehensive lifecycle inventory of urban transport modes in China. It differs from existing LCA models in that it decomposes major urban transport modes into capital and operational units that are consistent with planning analysis. For example, units of calculations are urban expressway lane-kms rather than tons of cement and steel. Standard outputs of transportation demand models can be easily adapted into input of the model.

FIGURE 3: SYSTEM BOUNDARY OF LCA



The comprehensiveness of this model is constrained by data availability. The boundary of calculation is represented by the dashed box in Figure 3. The disposal (end-of-life) phase of vehicles and infrastructures are excluded from this model due to very limited data about the numerous possible pathways of this phase. This is not a special case for China. Delucchi (2005)'s summary of major industrial and academic transportation LCA efforts shows that few include disposal of vehicles.

Moreover, due to the difficulty in collecting data on non-CO_2 GHG emissions, this model attempts to include only four major types of GHGs (CO_2, CH_4, N_2O and HFC-134a) since they represent the vast majority of global warming effect from transportation-related GHG emissions. CO_2 equivalency (CO_2e) is used as an aggregate measure of all GHGs. According to Weigel et al (2010), none of the publicly available transportation LCA tools calculate perfluorocarbons (PFCs) or sulfur hexafluoride (SF_6), two of the six Kyoto Protocol GHGs (the others are the previously mentioned carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O) and hydrofluorocarbons (HFCs)). In fact, most tools surveyed by Weigel et al (2010) limit non-CO_2 GHG emissions calculations to subsets of the vehicle types covered.

Finally, this model supports mainstream and major emerging modal technologies to the extent that extensiveness is supported by data availability. For example, considering availability of fuels and maturity of heavy-duty engine technologies, the current inventory/model includes the compressed natural gas (CNG) bus but not the liquefied petroleum gas (LPG) bus. This is also consistent with the market penetration of the two technologies - CNG buses are much more common than LPG buses across the world and in China,[3] although it may not be the case of every Chinese city (e.g., Guangzhou currently uses more LPG buses than CNG buses).

It is also important to note that on one hand, emission factors across regional power grids in China are different; on the other hand, power grids across China are increasingly interconnecting to each other (Zhou et al 2010), meaning that regional difference in grid carbon intensity will disappear eventually as electricity is being traded across the whole nation. To determine the lifecycle GHG emissions from use electricity at any given urban area in China, one should probably consider power emission factors of both the regional grid and the national average.

2.2 Spreadsheet tool

A spreadsheet tool titled "Lifecycle Assessment for Urban Transport Systems in China" has been developed according to the above mentioned framework. This tool does not compare alternative scenarios of urban transport system development in one step. Instead, for each alternative scenario, the user inputs relevant data, runs the calculations, and saves the data input and results as a new sheet (named by user) within the same file.

---

[3] See http://www.cleanairnet.org/infopool/1411/propertyvalue-17732.html and http://www.cleanairnet.org/infopool/1411/propertyvalue-17731.html.

The spreadsheet tool includes three parts: user input, data/parameters and result. To run the tool, user enters all the input fields in user input sheet, and then clicks "Run" at the end of sheet. Results are then generated and rendered in a separate sheet named by the user. Appendix 4 shows the contents in each sheet of the tool. Below is a brief description of each part and use instructions.

In the user input part, user describes the projected/planned urban transport system in eight sections.

- First, user chooses a study period length up to 30 years. Allowing a future projection that is too remote has three problems. First, the travel demand projections will be extremely unreliable due to long-term evolution of population, land use, and other parameters excluded by demand models; second, there will be many more unforeseen breakthroughs in technology in the more distance future, making the current projections less relevant; third, the environmental implications and economic cost of GHG emissions in the remote future can be dramatically different from that emitted in the near future.
- Second, user quantifies new investment of vehicle capital and existing stock and new investment of infrastructure at the beginning of the study period ("Year 0"). Existing infrastructure stock is needed for estimating energy and GHG impacts of infrastructure operation and maintenance.
- Third, user inputs aggregated traffic forecasts by mode-year from Year 1 to the number of years specified by the study period.
- Fourth, user inputs replacement and additional vehicles needed each year during the study period.
- Fifth, user inputs replacement and additional infrastructures needed each year during the study period.
- Sixth, user inputs retirement/disposal of infrastructures needed each year during the study period.
- Seventh, user inputs expected average annual percentage decreases/changes in emission factors of electricity during the study period.
- Finally, user inputs expected average annual percentage gain/changes in fuel/power economy of vehicles during the study period.

To make the emission inventory transparent to users, the data/parameters part present energy consumption and GHG emission inventories collected by this project in three data sheets. Sheet A presents emission factors of fuel/power. Sheet B presents average vehicle fuel economy or power consumption rates. Sheet C presents lifecycle energy use and GHG emissions of capital production/construction and non-operation processes.

To compile a time/location-specific inventory of lifecycle GHG emissions for the various parts and processes in Chinese urban transport, a mix of direct and indirect data sources and estimate processes are used. In general, estimates from first-hand data and peer-reviewed literature are given higher priority than those from “gray” literature. Due to the lack of sufficient information, a significant portion of infrastructure emission parameters are transferred (with modification) from U.S. estimates (e.g. Chester, 2008) or roughly estimated based on cost relationships (e.g. Wang, 2008 & 2010). At this point, detailed emission inventory by type of GHG (e.g., CO_2, CH_4, N_2O, etc.) is unavailable, so the currently inventory focuses on CO_2e. Reports on by the two domestic data-collection teams are attached in Appendixes 5 and 6. Appendix 7 summarizes the final estimated values, estimation methods and sources of data in the three data sheets.

The results are stored in a separated new sheet, which contains all input data and a table of the total energy consumptions and GHG emissions over the study period by year. Appendix 3 explains the details of the calculation methods.

3 MODEL TEST AND SENSITIVITY ANALYSIS

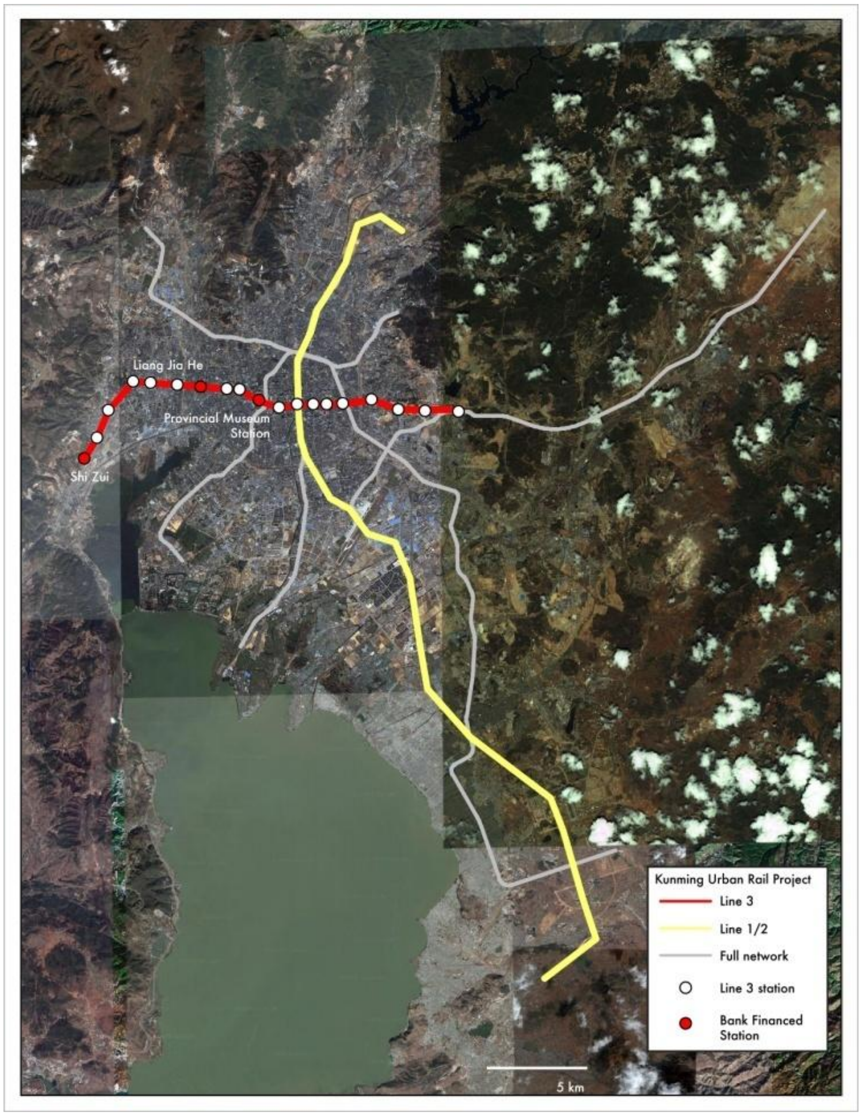
To test and fine-tune the model/methodology, and make preliminary estimates of lifecycle GHG emissions, we apply the framework, model and data collected to one proposed urban rail project in China. As described, the basic inputs to the spreadsheet model are the outputs of the travel demand model used to evaluate the proposed urban rail project.

3.1 CASE STUDY DESCRIPTION

The test case for the spreadsheet tool is a proposed urban rail project in the city of Kunming, China. The municipality has an estimated population of 5.7 million (with about 3 million residing in the central city area), 1 million motor vehicles, 3,000 buses, and gross domestic product (GDP) of RMB120 billion. Constrained by lakes and mountains, the municipality has promulgated a master plan that promotes high density, compact land use development.

The city is notable for its sustained focus on public transport. It was one of the first cities in China to implement a network of bus priority corridors. As elsewhere in China, Kunming has witnessed a significant increase in the use of motor vehicles in the decade from 1994 to 2005. With the rapid growth of the city's extent, population and motorization, Kunming is now confronting a rapid rise in traffic congestion. Travel demand continues to increase rapidly. In response, the city has planned, and gained approval for, a massive investment in urban rail. The proposed system would encompass six lines operating on a total length of 162.6 km. The two lines to be constructed first are in corridors with some of the city's highest bus ridership. The first line (Lines 1 & 2) is currently under construction, and the World Bank has recently approved a loan for the second line (Line 3). The World Bank financed line runs 19.54 km on a major east-west axis through the heart of the Kunming Central Business District (CBD), shown in red in Figure 4.

FIGURE 4: KUNMING URBAN RAIL PROJECT



3.2 MODEL APPLICATION

To analyze the life cycle impacts of this project, we propose two alternative scenarios to be compared in the spreadsheet tool, namely the build (subway Line 3) and no-build scenarios. In this preliminary model calculation, the two scenarios are simplified as the addition of Line 3 or its bus-plus-car substitute, assuming the rest of the urban transport system constant. The study period is set to 30 years.

Major technological or supply-side assumptions are shown in Table 1. Two important assumptions, grid carbon intensity and rail system power use rate, are explained in detail here. Grid carbon intensity (GHG emitted per kWh used) determines how much GHG will be emitted given amount of electricity consumed. Mainland China has six regional power grids. The South China Grid (SCG), to which Kunming connects, is the least carbon intensive regional grid, thanks to its relatively high share of hydro power.

According to iCET (2011), the SCG's overall carbon intensity (for power generation only) in 2008 was 573.5 g/kWh, in which 64.4% was thermal, 30% was hydro, 5.5% was nuclear, and 0.1% was wind and other forms of power. iCET also assumes that on average upstream GHG emissions account for about 5% of total upstream and generation emissions and that T&D emissions account for about 6.4% of total lifecycle emissions. Assuming upstream GHG emissions of hydro and nuclear powers in the SCG are the same as in Korea (Lee et al 2004, Table 9) – 25.2 and 2.77 g/kWh, respectively, we estimate the total lifecycle GHG emission of the SCG to be 653 g/kWh.

However, primarily due to Guangdong Province's large demand of power, the SCG has been a net importer of power from other regional grids in the past several years, especially from the Central China Grid since the Three Gorges Power Plant were put into use. Across China, inter-grid energy transfer is on the rise. The Chinese regional power grids were all connected by 2006. The capacity of inter-grid transfer is growing rapidly due to the Central Government's strategy of transmitting power from Western China to the Central and Eastern parts.[4] This is in contrast to the deeply fragmented U.S. grid systems. Depending on how we treat the 'marginal' power consumption of the Kunming rail project, we consider the national average power carbon intensity as a viable (especially in the long term) alternative to the grid-level average for calculating Kunming urban rail's carbon footprint. As described in Appendix 7, the national average lifecycle power carbon intensity is 1072 g/kWh (Ou et al 2011).

Power consumption of a rail system depends largely on system technology (e.g., efficiency of electric motors and ability to recycle brake energy) and the need for heating, ventilation and air conditioning (HVAC). However, detailed decomposed energy uses of a rail system are difficult to determine based on available data. This study chooses to estimate the average system power use per rail car km. In general, urban heavy rail systems in Mainland China have power use rate of about 6 kWh/car-km, as indicated by the projected power use rate of the Beijing Metro Line No. 10 (北京城建设计研究总院, 北京地铁集团, 2003) and the reported average power consumption of the Shanghai Metro system in 2007[5]. Sharing lots of similarities with the Beijing and Shanghai systems, the Hong Kong metro system was able to reduce energy consumption from 5.94 kWh per revenue car-km in 2005 to 4.86 kWh in 2009, mainly through replacing motor-alternators with static inverters, optimizing train speed and coasting, adjusting temperatures on trains, and reducing station cooling.[6] With the installation of energy-efficient LED lights on trains and in stations, the power consumption rate can be even lower in the future for the Hong Kong metro system.

[4] See, e.g., http://www.reuters.com/article/2011/04/26/china-power-idUSL3E7FQ03D20110426.
[5] See http://jjyxfx.moc.gov.cn/ShowNews.asp?ID=289.
[6] See http://www.mtr.com.hk/eng/sustainability/sustainrpt/env-acc-resource-ele.htm.

Due to Kunming's mild climate, the need for HVAC for its underground rail system should be less than cities like Beijing and Shanghai. However, it is hard to be precise about how much lower it will be. 5 kWh/car-km is assumed to be the power consumption rate of Kunming's metro system.

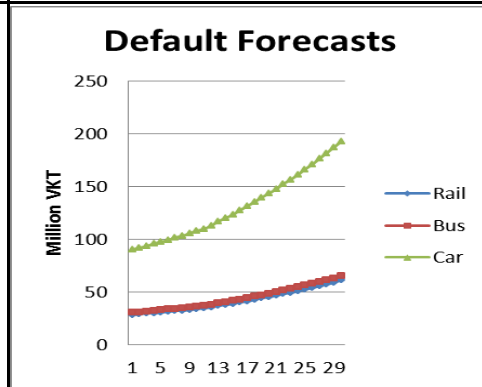
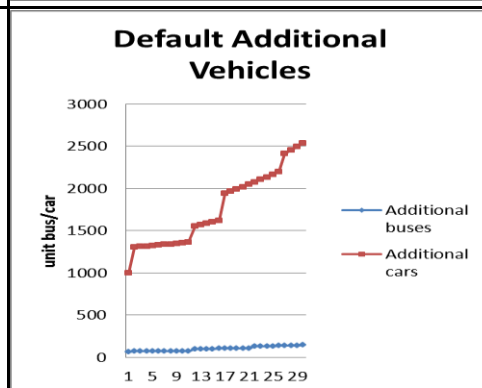
TABLE 1: BASELINE/DEFAULT SUPPLY-SIDE ASSUMPTIONS

Global assumptions	
Grid carbon intensity	653 g CO_2e/kWh
Build scenario	
Number of rail cars	144
Rail ROW in km	19.54
Rail stations (underground)	17
Depot space per rail car	500 m^2
Rail system energy consumption	5 kWh/rail-car-km
No build scenario	
Bus average daily mileage	162 km
Car average daily mileage	20 km
Average life of bus	10 yrs
Average life of car	15 yrs
Depot space per bus	75 m^2
Attributable parking spaces per car	1
Bus (diesel) fuel economy	0.4 L/km
Car (gasoline) fuel economy	0.085 L/km

The demand side assumptions are presented in Table 2. As described, the purpose of the tool is to use the outputs of a travel demand model as inputs for the spreadsheet tool. For a travel demand model that has already been fully specified and used in a traditional project evaluation, it is generally a simple task to output passenger movements by mode for a typical day. The typical unit for this exported data would be in passenger kilometers travelled: the total number of kilometers that passengers travelled by metro, or by car, or on foot, etc. Emissions are not, however, directly generated by passenger kilometers. They are generated by vehicle kilometers – the number of kilometers that a given bus, car, or metro vehicle travels in a given day. Relating one to the other requires some knowledge of how many passengers are transported in a given vehicle – the load or occupancy. We made some estimates of these loading factors in Kunming for a preliminary run of the model. Given the importance these estimates play, variations of potential loading were developed for the sensitivity analyses described later.

In addition to load factors, the model requires estimates of infrastructure requirements for various scenarios. For the build scenario – these estimates were relatively straightforward and spelled out in detail in the urban rail feasibility study. For the alternative bus-and-car scenario, the marginal infrastructure additions required in the no-build scenario had to be estimated. These include new bus purchases, bus depots, new private vehicle purchases, new km of arterial road, and new parking spaces.

TABLE 2: BASELINE/DEFAULT DEMAND-SIDE ASSUMPTIONS

Rail-to-road passenger-km conversion	74% bus, 15% car
Forecasted VKT	
Additional vehicles	
Initial vehicles	628 buses, 15043 cars
Road lane (km)	215.7
Bus depot (sqm)	100725
Car parking spaces	32155
Bus average load factor	20/bus
Rail average load factor	29/rail car, compared to standard capacity of 243 (40 seated) and crush capacity of 313 per rail car

3.3 BASELINE RESULTS

Using the inputs of build and no-build scenarios, the tool was able to calculate the lifecycle GHG emissions and operational energy consumptions of both scenarios. Results are shown in Tables 3 and 4. Under the default assumptions, 30-year total GHG emissions are very close for the build and no-build scenarios (4.47 and 4.62 million metric tons of CO_2e, respectively), with operational GHG emissions accounting for 91% of full lifecycle emissions for the build scenario and 69% for the no-build scenario.

TABLE 3: BUILD SCENARIO WITH DEFAULT ASSUMPTIONS

	Operational Energy Consumption			Lifecycle GHG Emissions
	Electricity (kWh)	Gasoline (L)	Diesel (L)	CO2e (kg)

Year 0	0	0	0	3.86E+08
Year 1	143103419.7	0	0	93446533
Year 2	145965488.1	0	0	95315464
Year 3	148884797.9	0	0	97221773
Year 4	151862493.8	0	0	99166208
Year 5	154899743.7	0	0	1.01E+08
Year 6	157997738.6	0	0	1.03E+08
Year 7	161157693.3	0	0	1.05E+08
Year 8	164380847.2	0	0	1.07E+08
Year 9	167668464.2	0	0	1.09E+08
Year 10	171021833.4	0	0	1.12E+08
Year 11	174442270.1	0	0	1.14E+08
Year 12	179675538.2	0	0	1.17E+08
Year 13	185065804.4	0	0	1.21E+08
Year 14	190617778.5	0	0	1.24E+08
Year 15	196336311.8	0	0	1.28E+08
Year 16	202226401.2	0	0	1.32E+08
Year 17	208293193.2	0	0	1.36E+08
Year 18	214541989	0	0	1.4E+08
Year 19	220978248.7	0	0	1.44E+08
Year 20	227607596.2	0	0	1.49E+08
Year 21	234435824.1	0	0	1.53E+08
Year 22	241468898.8	0	0	1.58E+08
Year 23	248712965.7	0	0	1.62E+08
Year 24	256174354.7	0	0	1.67E+08
Year 25	263859585.4	0	0	1.72E+08
Year 26	271775372.9	0	0	1.77E+08
Year 27	279928634.1	0	0	1.83E+08
Year 28	288326493.1	0	0	1.88E+08
Year 29	296976287.9	0	0	1.94E+08
Year 30	305885576.6	0	0	2E+08
TOTAL	6254271645	0	0	4.47E+09
Operational				4.08E+09

TABLE 4: NO-BUILD SCENARIO WITH DEFAULT ASSUMPTIONS

	Operational Energy Consumption			Lifecycle GHG Emissions
	Electricity (kWh)	Gasoline (L)	Diesel (L)	CO2e (kg)
Year 0	0	0	0	3.99E+08
Year 1	21003360	7672035.25	12220758.2	97682123
Year 2	21003360	7825475.955	12465173.36	1.04E+08
Year 3	21003360	7981985.474	12714476.83	1.05E+08
Year 4	21003360	8141625.183	12968766.37	1.07E+08
Year 5	21003360	8304457.687	13228141.69	1.08E+08
Year 6	21003360	8470546.841	13492704.53	1.1E+08
Year 7	21003360	8639957.778	13762558.62	1.11E+08
Year 8	21003360	8812756.933	14037809.79	1.13E+08

Year 9	21003360	8989012.072	14318565.99	1.14E+08
Year 10	21003360	9168792.313	14604937.31	1.16E+08
Year 11	21003360	9352168.159	14897036.05	1.18E+08
Year 12	21003360	9632733.204	15343947.13	1.25E+08
Year 13	21003360	9921715.2	15804265.55	1.27E+08
Year 14	21003360	10219366.66	16278393.51	1.3E+08
Year 15	21003360	10525947.66	16766745.32	1.33E+08
Year 16	21003360	10841726.09	17269747.68	1.36E+08
Year 17	21003360	11166977.87	17787840.11	1.42E+08
Year 18	21003360	11501987.2	18321475.31	1.46E+08
Year 19	21003360	11847046.82	18871119.57	1.49E+08
Year 20	21003360	12202458.23	19437253.16	1.52E+08
Year 21	21003360	12568531.97	20020370.76	1.56E+08
Year 22	21003360	12945587.93	20620981.88	1.62E+08
Year 23	21003360	7825475.955	21239611.33	1.66E+08
Year 24	21003360	13733974.24	21876799.67	1.7E+08
Year 25	21003360	14145993.46	22533103.66	1.74E+08
Year 26	21003360	14570373.27	23209096.77	1.78E+08
Year 27	21003360	15007484.47	23905369.68	1.85E+08
Year 28	21003360	15457709	24622530.77	1.89E+08
Year 29	21003360	15921440.27	25361206.69	1.94E+08
Year 30	21003360	16399083.48	26122042.89	1.99E+08
TOTAL	630100800	329794426.6	534102830.2	4.62E+09
Operational				3.18E+09

3.4 Sensitivity analysis

Sensitivity analysis is important due to the uncertainty in inputs and parameters. After obtaining the initial results, standard sensitivity tests were first carried out for tool parameters, whereby a ±20% variation was applied to each of the parameters of the spreadsheet tool to see how sensitive the lifecycle emissions are given such variations. Appendix 8 shows the results. From this initial testing, a series of supply-side (technological) factors that were most critical to results were identified. These factors are the carbon intensity of the electricity grid, the operational energy efficiency of the metro system, and the fuel efficiency of the bus system. These supply-side factors, together with major demand-side assumptions, are given more in depth sensitivity testing, described below.

To highlight how major assumptions on model parameters and input may together drive the result of comparing the lifecycle GHG emissions between the build and no-build scenarios, Table 5 presents three groups of alternative assumptions based on reasonable variability in key parameters and demand forecast inputs. Default assumptions are those used to produce the baseline results previously, while "pro-rail" and "pro-road" assumptions represent groups of assumptions that may tilt the comparison to one of the two scenarios (build and no-build).

The three important supply-side factors mentioned above are varied from their baseline values. For grid carbon intensity, the national average lifecycle GHG emissions per kWh electricity consumed is used as a pro-road assumption, while the default and the pro-rail assumptions remain the lifecycle GHG emission factor of the SCG. Bus fuel efficiency is assumed to be 0.3 L/vkt in the pro-road case and 0.5 L/vkt in the pro-rail case, representing more and less frugal/efficient bus operation, respectively. As to the alternative assumptions on rail energy consumption, we use in the pro-rail case 4 kWh/car-km, representing a more frugally designed and operated subway in Kunming (e.g., minimum HVAC). In the pro-road case, we assume 6 kWh/car-km, the current energy use rate of the Beijing and Shanghai's systems.

On the demand forecast side, a variety of factors can affect the input to the spreadsheet tool greatly, including how the rail trips are replaced in a no-build scenario, transit vehicle load factors, and the respective vehicle and infrastructure requirements in the no-build scenario, all presented in Table 5.

It is important to note that we use "frozen technology" for 30 years in this sensitivity analysis. This is obviously unrealistic – it is undoubtedly true that over the next 30 years, the fuel efficiency of bus and metro systems in China, as well as the carbon intensity of the electricity grid are likely to change substantially. The spreadsheet developed allows for simple assumptions of how such factors may change at constant rates over the study period. However, without carefully developing scenarios of technological change for Chinese bus and metro systems together, we might unfairly bias our analysis towards one or the other mode if we assume, for example, substantial improvements in the emission factor of the grid without assuming a comparable increase in bus fuel efficiency. Developing and analyzing scenarios of these types of changes in Chinese cities was not carried out for this study.

Table 6 presents the results of sensitivity analysis under the baseline/default as well as two alternative assumptions. The results seem quite sensitive to the assumptions, showing the strong effects of the different parameters and model inputs. Under the default/baseline assumptions, the ratio between GHG emissions in the build and no-build scenarios is close to 1. But the ratio drops to 44.3% under the pro-rail assumptions and rises to more than 3 given the pro-road assumptions. Such great sensitivity of alternative assessment results to supply- and demand-side assumptions indicates the input-driven nature of transport LCA. As the capital emissions (embodied in infrastructure and vehicles) are small portions of the overall emissions in 30 years in the build scenario, the fact that rail infrastructures are typically built to last longer than 30 years does not seem to be able to make significant difference.

Table 5: Alternative assumptions

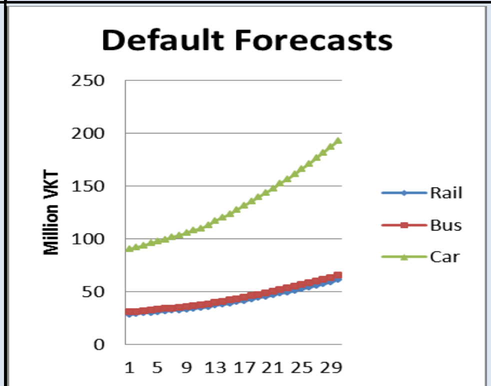
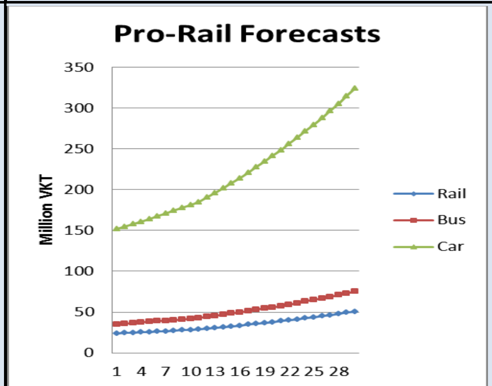
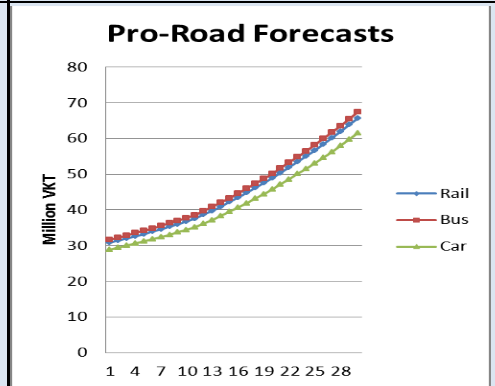
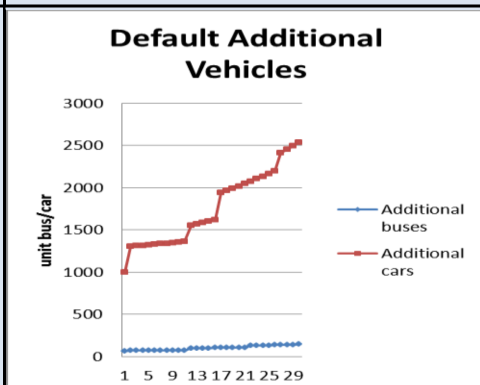
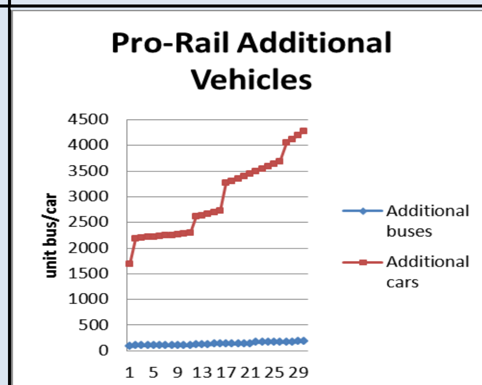
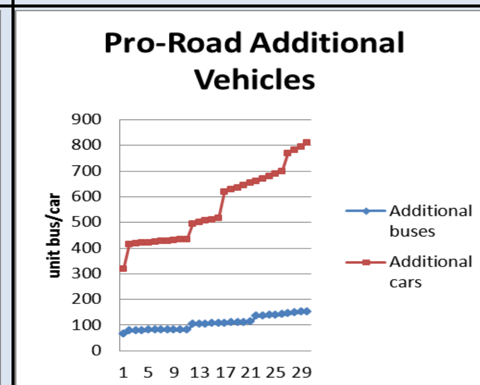
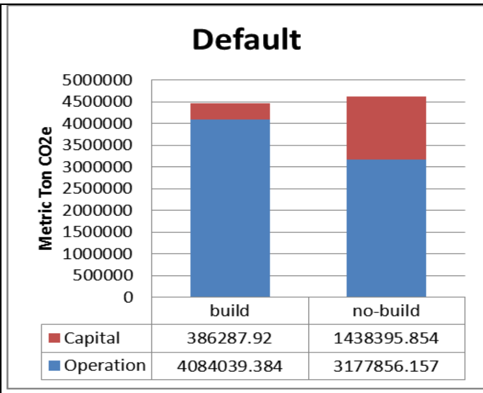
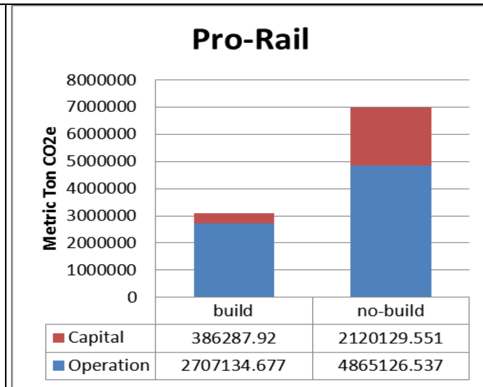
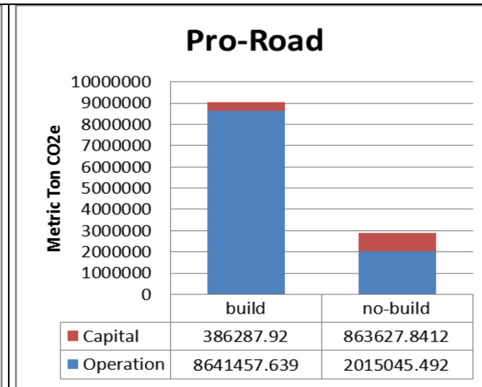
<table>
<tr><th></th><th>Default</th><th>Pro-Rail</th><th>Pro-Road</th></tr>
<tr><td>Grid carbon intensity</td><td>653 g CO_2e/kWh</td><td>653 g CO_2e/kWh</td><td>1072 g CO_2e/kWh</td></tr>
<tr><td>Vehicle energy efficiency</td><td>5 kWh/vkt for rail
0.4 L/vkt for bus</td><td>4 kWh/vkt for rail
0.5 L/vkt for bus</td><td>6 kWh/vkt for rail
0.3 L/vkt for bus</td></tr>
<tr><td>Rail-to-road pkt shift</td><td>74% bus, 15% car</td><td>64% bus, 25% car</td><td>84% bus, 5% car</td></tr>
<tr><td>Avg. load factors</td><td>20/bus, 29/rail car</td><td>15/bus, 35/rail car</td><td>22/bus, 27/rail car</td></tr>
<tr><td>Forecasted VKT</td><td>
</td><td>
</td><td>
</td></tr>
<tr><td>Initial vehicles</td><td>628 buses, 15043 cars</td><td>724 buses, 25290 cars</td><td>649 buses, 4796 cars</td></tr>
<tr><td>Additional vehicles</td><td>
</td><td>
</td><td>
</td></tr>
<tr><td>Road lane km</td><td>215.7</td><td>316.6</td><td>130.9</td></tr>
<tr><td>Bus depot (sqm)</td><td>100725</td><td>116100</td><td>104025</td></tr>
<tr><td>Car parking spaces</td><td>32155</td><td>54058</td><td>10252</td></tr>
</table>

TABLE 6: RESULTS UNDER ALTERNATIVE ASSUMPTIONS

Results under alternative assumptions			
Build/no-build ratio	96.8%	44.3%	313.6%
Capital/operation portions	8.6%/91.4% (build) 31.2%/68.8% (no build)	12.5%/87.5% (build) 30.4%/69.6% (no build)	4.3%/95.7% (build) 30.0%/70.0% (no build)

4 Conclusions and discussion

4.1 Implications of model test result

Based on estimated lifecycle GHG emission inventory in China, the Excel-based spreadsheet model provides a simple, transparent, fast, and inexpensive way to help facilitate reasonable direction for alternative assessment.

Despite limitations in both the inventory data and transport modeling that will be explained below, our results suggest that urban rail projects, particularly in areas powered primarily by coal generated electricity, are likely not a 'slam dunk' from an emissions perspective. In the Kunming Subway Line 3 case, emissions from a road-based alternative were comparative to the alternative metro case under our baseline assumptions. Although there are reasons to suspect that alternative assumptions and more careful modeling of the impacts of congestion and long term development impacts might help tip the scales in favor of metro, the note of caution remains valid.

For policy, some lessons are clear. The first is the importance of operational emissions. Initial model runs suggest that capital (infrastructure and vehicle embodied) emissions for the build scenario are no more than 12.5% of overall emission for a 30 year life span, which suggests that the analytical and implementation focus from an emissions perspective should be on the operational side. It seems important to carefully consider all the ways that operational energy consumption can be reduced, including:

- The carbon intensity of the source of electricity to be used over the life of the project (although this strategy is weakened after regional grids are interconnected – carbon intensity of all grids will converge to a common national value);
- Considering elevated alignments in order to reduce energy consumption related to underground operation, e.g., lighting and ventilation;
- Close scrutiny of the operational energy consumption of the metro system. Factors that can impact this are wide ranging and include stop spacing, maximum speed, acceleration/deceleration rates, regenerative braking technology, etc.

Once the decision to proceed with an urban rail project has been made, this research provides further evidence of the importance of ensuring that all efforts are made to ensure its success. This includes a variety of measures including focusing on bus/rail integration (through integrated fares, high quality transfer stations, and joint service planning) to ensure that bus and rail systems work as an integrated, efficient system; supporting transit oriented development; and ensuring that other transport policies in the city (parking, congestion management, etc.) work to support the metro systems. These crucial points are described in a companion World Bank document entitled "Urban Rail in China."

Finally, as stated in the beginning the report, cities undertake urban rail projects for many reasons of which energy and GHG concerns are only one element. These include mitigating traffic congestion and reducing overall passenger travel time for both metro users and non-users, improving the reliability and comfort of transport service to attract and retain "choice customers"; and facilitating compact city development. Metro systems may also provide other potentially significant co-benefits such as improved air quality, reduced noise, and lower traffic fatalities.

Overall, this work is a step forward as a first attempt to operationalize the pioneering life cycle work of Chester (2008) in the Chinese context. Although limitations in data and modeling means further research will help to refine and strengthen project conclusions, an important value of this work is pointing out most crucial factors that affect lifecycle GHG emissions – electricity carbon intensity, rail and bus energy efficiency, and demand forecast. For example, if this test project is carried out in a different Chinese city, it is much more likely that the build scenario will perform worse than the no-build alternative, because few other Chinese cities have a combination of low-carbon electricity and mild climate as Kunming does. In those cities, for the purpose of climate change mitigation, the bus-car alternative would be more attractive to rail, especially the underground systems.

4.2 International comparison

A seemingly surprising finding of this study is the smaller share of capital emissions in overall lifecycle emissions compared to the findings in the U.S. (Chester 2008, Chester and Horvath 2009). A breakdown of lifecycle GHG/energy impacts in the U.S. by Chester (2008) and Chester and Horvath (2009) shows that capital emissions constitute about 23% of the energy consumption and 36% of the GHG emissions of the lifecycle energy/GHG impacts for the Bay Area Rapid Transit (BART) system. However, according to Table 6, in the Kunming case, capital emissions are likely less than 10% of the total rail system lifecycle GHG emissions.

There are at least two major reasons this might be true. First, the carbon intensity of electricity that the BART uses (271 g/kWh for Bay Area mix, compared to 351 g/kWh of the California electricity production mix and 632 g/kWh of the Massachusetts mix) is far lower than the Kunming rail operates with (653 g/kWh for SCG and 1072 g/kWh for national average). Second, parking garage, equivalent to more than 20% of infrastructure construction emissions, is part of the BART capital investment but not in Kunming.

4.3 Limitations

The major weakness of the current model/tool is the completeness and level of precision of its lifecycle GHG emissions inventory. Detailed emissions inventory by type of GHG (e.g., CO_2, CH_4, N_2O, etc.) is currently unavailable. A significant portion of infrastructure emission parameters are transferred (adjusted) from U.S. estimates (e.g. Chester, 2008) or roughly estimated based on cost relationships (e.g. Wang, 2008). Future estimates of the lifecycle emissions inventory based on detailed domestic data will make the tool more credible. Certain data are collected and used in an aggregate way, making the tool insensitive to some design and/or operational changes. For example, rail system energy consumption data are measured in aggregate. Obviously, to tie emissions from the infrastructure at an average rate to VKT will hurt systems that run a lot of trains over the same length of track.

In addition, the impacts of congestion are not modeled to a high degree of sophistication. The demand forecast used is from an all-day model, capturing travel at an aggregate level that makes it difficult to separate out the growing impact of congestion as vehicle ownership increases. In the long run, this congestion effect might be expected to degrade bus performance, driving more passengers to private vehicles in the no-build scenario as compared with a rail system insulated from the impact of congestion. However, for the Kunming Line 3 case in particular, this effect may not be as pronounced as it might be since the corridor above rail Line 3 is already largely equipped with a two lane busway, shielding to some degree the public transport system from the growing effects of congestion.

Results presented in this particular iteration of the model also suffer from the underlying limitations of the demand model from which we draw travel data.

First, car ownership is not directly modeled. Given the rapid increase in motorization in Chinese cities, this has the potential to generate significant distortions in the later years of the study period. Studies in the United States and elsewhere have shown that the quality of public transport infrastructure is unlikely to have a large effect on the ownership of a household’s first car. As incomes increase in China, owning a car is beginning to be viewed as a necessity and status symbol by those who can afford it, and the quality of transport infrastructure on its own is probably unlikely to significantly affect this. However, in other contexts the effect of high quality alternative transportation has been shown to have a significant effect on second and even third car ownership, as these can be viewed as more truly "discretionary" items that can be more directly influenced by a high quality transport modal alternative.

Second, development impacts of the metro are not modeled in the underlying transport model. The assumed distribution of land use is the same in the metro and bus/car scenarios for all modeled years, and there is no feedback between the transport and land use scenarios. Experience seems to indicate that metro systems have the potential – in the presence of a supportive environment – to change land use in way that is supportive of public transport. This, indeed, is one of many reasons that city leaders often elect to construct a metro system. This effect is not modeled in our transport model – but neither is it modeled in the majority of commercial transport models being used in practice today (in China or elsewhere).

4.4 Future research

One avenue for future research will be the further development of the emissions factors used in the current model, many of which had to be adapted for foreign studies and would benefit from further analysis.

Given that the tool is still in the pilot phase, it would be strengthened by applying it to a variety of urban transport projects in other Chinese cities. Ideally, these future model applications would include the ability to model congestion and potentially land use impacts with a greater degree of sophistication. This type of follow up is already planned, based on some planning studies the Bank has been supporting in a variety of other cities in China.

REFERENCE

Cherry, C.R., J.X. Weinert and X. Yang. 2009. Comparative environmental impacts of electric bikes in China. *Transportation Research Part D* 14, 281-90.

Chester, M.V. 2008. Life-cycle environmental inventory of passenger transportation modes in the United States. *PhD Dissertation* University of California, Berkeley, CA.

Chester, M.V. and A. Horvath. 2009. Environmental assessment of passenger transportation should include infrastructure and supply chains. *Environmental Research Letter* 4 024008.

Chester, M.V., A. Horvath and S. Madanat. 2010. Comparison of life-cycle energy and emissions footprints of passenger transportation in metropolitan regions. *Atmospheric Environment* 44, 1071-9.

Delucchi, M.A. 2003. A lifecycle emissions model (LEM): Lifecycle emissions from transportation fuels, motor vehicles, transportation modes, electricity use, heating and cooking fuels, and materials. ITS-Davis Publication No. UCD-ITS-RR-03-17-MAIN REPORT.

Delucchi, M.A. 2005. A multi-country analysis of lifecycle emissions from transportation fuels and motor vehicles. ITS-Davis Publication No. UCD-ITS-RR-05-10.

Economic Input-Output Life Cycle Assessment (EIO-LCA). 2009. US 1997 industry benchmark model. Carnegie Mellon University Green Design Institute.

Hackney, J. and R. de Neufville. 2001. Life cycle model of alternative fuel vehicles: emissions, energy, and cost trade-offs. *Transportation Research Part A* 35(3), 243-66.

iCET. 2011. Electric vehicles in the context of sustainable development in China. United Nations Department of Economic and Social Affairs, Commission on Sustainable Development, Nineteenth Session, New York, 2-13 May 2011. Background Paper No.9, CSD19/2011/BP9. Available at http://www.un.org/esa/dsd/resources/res_pdfs/csd-19/Background-Paper-9-China.pdf.

Lee, Kun-Mo, Sang-Yong Lee, and Tak Hur. 2004. Life cycle inventory analysis for electricity in Korea. *Energy* 29, 87-101.

Leontief, W. 1970. Environmental repercussions and the economic structure: an input-output approach. *The Review of Economics and Statistics* 52, 262-71.

Ogden, J.M., R.H. Williams and E.D. Larson. 2004. Societal lifecycle costs of cars with alternative fuels/engines, *Energy Policy* 32(1), 7-27.

Ou, X., X. Yan, and X. Zhang. 2011. Life-cycle energy consumption and greenhouse gas emissions for electricity generation and supply in China. *Applied Energy* 88, 289-297.

Wang, R. 2008. Autos, Transit and Bicycles: Transport Choices in Chinese Cities. Harvard University Ph.D. Dissertation.

Wang, R. 2010. Autos, Transit and Bicycles: Comparing the Costs in Large Chinese Cities, *Transport Policy*, 18:139-146.

Weigel, B.A., F. Southworth, and M.D. Meyer. 2010. Calculators to Estimate Greenhouse Gas Emissions from Public Transit Vehicles. *Transportation Research Record* 2143, 125-133.

Weiss, M.A., J.B. Heywood, E.M. Drake, A. Schafer and F.F. AuYeung. 2000. On the road in 2020: A lifecycle analysis of new automotive technologies. MIT Energy Laboratory Report EL 00-003.

Yan, X. and R.J. Crookes. 2009. Life cycle analysis of energy use and greenhouse gas emissions for road transportation fuels in China. *Renewable and Sustainable Energy Reviews* 13, 2505-2514.

Zhou, Xiaoxin, Jun Yi, Ruihua Song, Xiaoyu Yang, Yan Li, and Haiyan Tang. 2010. An overview of power transmission systems in China. *Energy* 35, 4302-4312.

北京城建设计研究总院，北京地铁集团。2003年6月。北京地铁十号线一期（含奥运支线）工程可行性研究报告。

城市道路照明设计标准, CJJ 45-2006。

公共停车场工程建设规范, 北京市地方标准 DB11/T 595—2008。

建筑照明设计标准, GB 50034-2004。

刘丽珍 侯凯。2009。CNG公交车用气指标的研究。煤气与热力，29(1)。

申威，张阿玲，韩为建。2006。车用替代燃料能源消费和温室气体排放对比。天然气工业，26（11）。

中华人民共和国交通部。2010-07-30。第三批节能减排示范项目推广材料之十六—北京公交集团新能源公交车。

APPENDIX 1: LEAD CONSULTANT TERMS OF REFERENCE

CHINA

Urban Transport, Energy Efficiency and Climate Change Management

Comparative Analysis of Energy Consumption and GHG Emissions
by Alternative Urban Transport Systems

Terms of Reference

Background

Now in its second year of execution, the World Bank-led "China Urban Transport, Energy Efficiency and Climate Change Program" is a multi-year, collaborative program of analytical works and implementation support activities that share the following specific objectives:

- To help China develop an energy efficiency and climate change management agenda in urban transport sector and operationalize energy and climate consideration into the processes of urban transport policy making, strategy formulation, program implementation and sector management, through collaborated analytical works;
- To help selected cities implement pilot actions and demonstrate how the urban transport sector could contribute to the energy efficiency and reduction of the growth of GHG emissions.
- To support Ministry of Transport to provide advice to cities on issues related to urban transport.

It is expected that the program would eventually evolve into a platform for all interested parties (e.g. national and local governments, academics, research institutions, industries, and international agencies) to come together to support the expanded range of activities with a common objective. The implementation of the program would be complemented by the other Bank urban transport operations in China, including the Global Environmental Facility (GEF) financed China Urban Transport Partnership Program and the on-going portfolio and upcoming pipeline of IBRD urban transport loans in various Chinese cities.

In the Year 2 of the program, the following activities are being carried out: (i) review of urban transport energy efficiency; (2) Public transport service planning and prioritization of public transport corridors in Beijing; (3) Analytical work for urban transport and land-use; (4) support to the government green vehicle initiatives; and (5) related to this terms of reference, a comparative analysis of energy consumption and GHG emissions by alternative urban transport systems including combinations of urban rail, bus, and private cars.

Over the last few years, China has experienced a wave of urban rail investments. A number of cities have developed urban rail systems (metro/subways and light rails) and a growing number of others are planning or constructing urban rail lines. In the context of climate change management, one expected benefit of the urban rail investments is their positive impact on global environment. Urban rails are normally considered to be more energy-efficient in operations than other land-based transport modes, such as buses and cars, because they use electricity to run, and carry out more loads per unit. However, urban rails require enormous amount of electricity and other sources of energy to build. Depending on the primary source of energy for electricity generation, it is not entirely clear if the full life cycle of urban rails is more energy-efficient and less GHG intensive than the full life cycles of bus and private car transport. To mainstream the climate consideration in urban transport planning and investments, it is important to be able to measure and understand the energy consumption and GHG impacts of alternative urban transport systems (i.e. alternative combinations of urban transport modes to serve a given travel market) during their entire life-cycles from construction, commission of operation to continuous operation till the end of the operation.

In FY09, through an urban rail sector review, the Bank team engaged with several Chinese cities on designing and implementing successful urban rail systems. A series of reports on different technical issues (planning and risks, rail technologies, land-use development, operations, private sector involvement and financing, service planning and integration with bus services) as well as an executive summary report were prepared and discussed with key national and city-level decision makers. Partly as a result of this effort, the Chinese authorities made the request to the Bank for a loan to finance urban rail development in the city of Kunming, Yunnan Province. This is the first time that the Chinese government requests the Bank to engage in urban rail sector.

Under Activity (5) highlighted above, the Bank's analytical work in urban rail sector is expected to focus on developing an understanding of the energy implication and full potential GHG emissions of an urban rail project under various land use and transport scenarios. Particularly, this study would seek answers to the following questions: (i) What are the main components (urban rail, bus, private car, bicycle, walking, etc.) of typical urban transport systems in Chinese cities and? (2) What are the energy consumption and GHG impacts of each component? (3) Considering the entire cycle effect and the Chinese context, is urban rail really superior to other land-based transport modes (e.g., trucks, buses and cars) on reducing GHG emissions? (4) From an economic perspective, is current urban rail development in China a truly most cost-effective approach compared to other land-based transport modes for addressing climate change problems? And (5) What components of the urban rail project present the biggest opportunities for reducing GHG emissions via technology innovation or policy intervention?

Consultant services from an individual international consultant are required for and the scope of works is specified in the following terms of reference.

Objective of Consultant Services

The consultant is expected to assist the World Bank team to develop a conceptual framework and suggest practical methodologies for a comparative analysis of energy consumption and GHG emissions by alternative urban transport modes serving a typical, (hypothetical) urban travel market in China.

Scope of Work

Task 1: Take a critical review of relevant literature on the subject from developed countries and comment on the relevance of the literature to the Chinese context.

Task 2: Develop a conceptual framework to decompose a defined urban transport system into components where life-cycle energy consumption and GHG emissions could be isolated and estimated. While the goal of this work is to develop a 'sketch analytical tool' to assist urban transport planning, it would be desirable for the structure of the analysis to follow the common GHG lifecycle analyses conducted for various purposes including Clean Development Mechanism (CDM) projects.

Task 3: Develop methodologies and tool (using spreadsheet) to estimate the energy consumption and GHG emissions for each component and synthesize to reach conclusions on the traffic performance and total energy consumption and GHG emissions of alternative urban transport systems.

As the focus of this work is to derive insights for urban transport planning, the consultant is encouraged to use existing standard GHG inventory tools,[7] and to apply the intellectual rigor on:

- *Developing possible GHG emission scenarios of an urban rail project at different phases including production, construction, and operation;*
- *Developing a model/methodology of estimating life-cycle GHG emissions under different scenarios, including different fuel mix supporting the production, construction, and operation process; and different short and long-term mode shift scenarios.*

Task 4. Where needed, coordinate with the Bank task team and other consultants and advise on the application of the framework, model and data collected to one proposed urban rail project in China (i.e. Kunming), to test and fine-tune the model/methodology, and estimate the life-cycle GHG emissions reductions for different scenarios. The consultant would not be expected to conduct this empirical study, but rather to direct and support others (see working arrangements).

Task 5: Based on the findings from the Tasks above, discuss the implication of urban rail development in Chinese cities. The main purpose of this discussion is to help the Bank, Chinese decision makers and the general public understanding the full implications of urban rail development on GHG emissions during its entire life cycle under the Chinese context. Other specific objectives include the following:

- *Understand what components (e.g. input and material production, infrastructure construction, infrastructure operation, fuel production, etc) contribute to different phases of an urban rail project in Chinese cities;*
- *Develop a model/methodology for estimating the level and amount of GHG emissions for each component in an Chinese urban rail project;*
- *Justify whether the popular urban rail development strategy is desirable for China to mitigate GHG emissions in future;*
- *Identify key potential areas of technology improvement and operation policy interventions in a urban rail project to reduce GHG emissions.*

Task 6: Prepare a final report summarizing the identified analytical issues, conceptual framework, methodologies, basic assumptions, simulation results, and conclusions. The final report should include the key outputs as follows:

- *Development of life-cycle energy and emissions inventories for a proposed urban rail project in Chinese Cities;*
- *Estimates of the full GHG emission reductions from the proposed urban rail project under different scenarios;*
- *Development of guidance on how to use the model/methodology in other urban rail projects;*
- *Development of strategic recommendations for implementing transit systems in Chinese cities targeting GHG emission reductions.*

Working arrangements

[7] There are a few local GHG inventory tools for cities, such as the Greenhouse gas Regional Inventory Protocol (G.R.I.P.) for Europe, the ICLEI Local Government GHG Protocol Project, CO_2 Grobbilanz/EMSIG, ECO2Region, and CO_2 Calculator.

It is expected that the international consultant will need support from one or more analysts who would collect existing literature, operationalize existing (usually spreadsheet models) GHG analysis tools and provide general support to the consultant. Such support will likely be needed both in China and locally, and will be hired by the Bank to support the international consultant.

Skills and Qualification

The consultant selected for the assignment should possess the following qualifications:

- A Ph.D. in transport economics and relevant fields, and strong academic background;
- Minimum of 20 years of research experience with urban transport policies, planning, modeling, and economic analysis;
- Familiarity with the urban transport related energy and climate change management issues, with relevant consulting experience as a plus;
- Both familiarity with the urban transport issues and practical experience in urban transport consulting in China would be a plus;
- Proficient in developing spreadsheet models for economic analysis.

Schedule and Reporting

The contract is expected to cover a total of 20 working days. The selected consultant should be prepared to begin work around January 2010. The contract period will be for 4 months, with a possibility to extend to another 6 months depending on the quality of work and the demonstrated need for further analytical works. The first contract would cover the first 20 working days only. The selected consultant is expected to mainly carry out the desktop work and if necessary visit China once to interact with Bank team and Chinese urban transport policy makers, planners and researchers. The duration of the visit should not be shorter than 5 days.

The consultant is expected to submit detailed technical notes following the visit and the draft final report by mid-April 2010, and Final Report by end May 2010. The consultant will be assisted by the World Bank Office in Beijing for logistics arrangements including arrangement of introductory meetings with key client agencies and cities.

APPENDIX 2: DATA COLLECTION TERMS OF REFERENCE

CHINA

Urban Transport, Energy Efficiency and Climate Change Management

Data Collection for the Comparative Analysis of Energy Consumption and GHG Emissions by Alternative Urban Transport Systems

Terms of Reference

Background

Now in its second year of execution, the World Bank-led "China Urban Transport, Energy Efficiency and Climate Change Program" is a multi-year, collaborative program of analytical works and implementation support activities that share the following specific objectives:

- To help China develop an energy efficiency and climate change management agenda in urban transport sector and operationalize energy and climate consideration into the processes of urban transport policy making, strategy formulation, program implementation and sector management, through collaborated analytical works;
- To help selected cities implement pilot actions and demonstrate how the urban transport sector could contribute to the energy efficiency and reduction of the growth of GHG emissions.
- To support Ministry of Transport to provide advice to cities on issues related to urban transport.

It is expected that the program would eventually evolve into a platform for all interested parties (e.g. national and local governments, academics, research institutions, industries, and international agencies) to come together to support the expanded range of activities with a common objective. The implementation of the program would be complemented by the other Bank urban transport operations in China, including the Global Environmental Facility (GEF) financed China Urban Transport Partnership Program and the on-going portfolio and upcoming pipeline of IBRD urban transport loans in various Chinese cities.

In the Year 2 of the program, the following activities are being carried out: (i) review of urban transport energy efficiency; (2) Public transport service planning and prioritization of public transport corridors in Beijing; (3) Analytical work for urban transport and land-use; (4) support to the government green vehicle initiatives; and (5) related to this terms of reference, a comparative analysis of energy consumption and GHG emissions by alternative urban transport systems including combinations of urban rail, bus, and private cars.

Over the last few years, China has experienced a wave of urban rail investments. A number of cities have developed urban rail systems (metro/subways and light rails) and a growing number of others are planning or constructing urban rail lines. In the context of climate change management, one expected benefit of the urban rail investments is their positive impact on global environment. Urban rails are normally considered to be more energy-efficient in operations than other land-based transport modes, such as buses and cars, because they use electricity to run, and carry out more loads per unit. However, urban rails require enormous amount of electricity and other sources of energy to build. Depending on the primary source of energy for electricity generation, it is not entirely clear if the full life cycle of urban rails is more energy-efficient and less GHG intensive than the full life cycles of bus and private car transport. To mainstream the climate consideration in urban transport planning and investments, it is important to be able to measure and understand the energy consumption and GHG impacts of alternative urban transport systems (i.e. alternative combinations of urban transport modes to serve a given travel market) during their entire life-cycles from construction, commission of operation to continuous operation till the end of the operation.

In FY09, through an urban rail sector review, the Bank team engaged with several Chinese cities on designing and implementing successful urban rail systems. A series of reports on different technical issues (planning and risks, rail technologies, land-use development, operations, private sector involvement and financing, service planning and integration with bus services) as well as an executive summary report were prepared and discussed with key national and city-level decision makers. Partly as a result of this effort, the Chinese authorities made the request to the Bank for a loan to finance urban rail development in the city of Kunming, Yunnan Province. This is the first time that the Chinese government requests the Bank to engage in urban rail sector.

Under Activity (5) highlighted above, the Bank's analytical work in urban rail sector is expected to focus on developing an understanding of the energy implication and full potential GHG emissions of an urban rail project under various land use and transport scenarios. Particularly, this study would seek answers to the following questions: (i) What are the main components (urban rail, bus, private car, bicycle, walking, etc.) of typical urban transport systems in Chinese cities and? (2) What are the energy consumption and GHG impacts of each component? (3) Considering the entire cycle effect and the Chinese context, is urban rail really superior to other land-based transport modes (e.g., trucks, buses and cars) on reducing GHG emissions? (4) From an economic perspective, is current urban rail development in China a truly most cost-effective approach compared to other land-based transport modes for addressing climate change problems? (5) What components of the urban rail project present the biggest opportunities for reducing GHG emissions via technology innovation or policy intervention?

An international consultant will be recruited to assist the World Bank team to develop a conceptual framework and suggest practical methodologies, model structure and input requirements for a comparative analysis of energy consumption and GHG emissions by alternative urban transport modes serving a typical, (hypothetical) urban travel market in China. The conceptual framework should be developed to decompose a defined urban transport system into components where life-cycle energy consumption and GHG emissions could be isolated and estimated.

It is expected that the framework, methodologies and models would be applied to one proposed urban rail project in China (likely Kunming), to test and fine-tune the model/methodology, and estimate the life-cycle GHG emissions reductions for different scenarios. Consultant services from a domestic consultant are required for the collection and simple analysis of data required for the models and methodologies. The following terms of reference specify the scope of work for the consultant services.

Objectives

The domestic consultant is expected to identify sources of relevant information and data available, and make an effort to collect as much data as possible and store the data in a certain format that would be convenient for the study team to estimate the life-cycle GHG emissions reductions for different urban transport technologies under various scenarios.

Data Requirements

The specific data requirements would eventually be worked out through the services of an international consultant and depend on the proposed conceptual framework, methodologies, and model structure. However, as a point of departure, the following data are proposed, and these will be supplemented by the recommendations from the international consultant services.

The data to be collected are relevant to the following **urban transport modes**:

- urban heavy rail;
- light rail;
- bus rapid transit (BRT);
- conventional bus transport; and
- private cars.

Main **stages of life-cycle** of urban transport technologies:

- Material and equipment production (i.e. power production, cement production, iron and steel production, vehicle manufacturing including original equipment manufacturing and assembling, production of other equipment such as rail tracks);
- Infrastructure construction;
- Service operations.

Data required for each stage of the life-cycle:

- Energy inputs (electric power, coal, liquid fuels, etc) and associated GHG emissions in physical quantities per unit of production (the data should be specific to the country sources of production such as German technology vs Chinese technology);
- Energy inputs (electric power and liquid fuel) and associated GHG emissions in physical quantities per unit of operation under different operating conditions (such as free-flow, congested, and heavily congested, to be defined).

Scope of Work

Task 1: Identify main sources of relevant information and data available through internet search and interview of relevant experts in the Bank, and quickly develop a data collection strategy, including the specific data to be collected and agencies to visit;

Task 2: Collect as much data as possible, analyze and verify to ensure adequate quality of data, and store the data in a format agreed with the Bank that would be convenient for the Bank study team to estimate the life-cycle GHG emissions reductions for different urban transport technologies under various scenarios.

Task 3. Provide general technical and liaison support to the international consultant selected for the study, where needed and appropriate.

Task 4: Prepare a summary report, documenting the sources of data, the data cleaning-up process, and the gaps that require further effort to fill.

Deliveries

The expected deliveries will include the following:

- Collected data with all necessary explanations of the data sources and comments in a structured database;
- A summary report as specified in Task 4.

Working arrangements

The entire study will be carried out by an international consultant (with separate TOR), one or two domestic consultants, and the Bank urban transport team. The selected domestic consultant under this TOR is expected to interact with the international consultant under the guidance of the Bank team leader.

Skills and Qualification

The consultant selected for the assignment should possess the following qualifications:

- A Master or Ph.D. in economics, transport, civil engineering, environment management, or relevant fields;
- Demonstrated proficiency in computer applications such as spreadsheet and database;
- Research experiences in urban transport, construction, and energy sectors will be a plus;
- Research experiences in computer modeling and economic analysis will be a plus.

Schedule and Reporting

The contract is expected to cover a total of 60 working days. The selected consultant should be prepared to begin work around January 2010. The contract period will be for 5 months, with a possibility to extend to another 6 months depending on the quality of work and the demonstrated need for further data collection and analysis works. The first contract would cover the first 60 working days only. The selected consultant is expected to mainly carry out the desktop work and, if necessary, visit data sources within China and the selected urban rail city (likely Kunming) where the empirical analysis of the energy consumption and GHG emissions by alternative urban transport systems is carried out.

The consultant is expected to submit the first draft database by end of March 2010, the second draft database and draft summary report by end of April 2010, and the final database and summary report by end of May 2010. The consultant will be assisted by the World Bank Office in Beijing for logistics arrangements including arrangement of introductory meetings with key client agencies and cities.

APPENDIX 3: CALCULATION METHODS OF THE SPREADSHEET TOOL

Each cell in the result page (except those in the "TOTAL" row, which is the total of the previous rows) sums the operational energy consumptions or lifecycle GHG emissions of vehicle and infrastructure.

For each year from Year 0 to Year N (length of study period specified in the "Input" sheet by the user), the vehicle energy/GHG impacts are obtained by adding together the impacts of each mode, which are calculated as below.

- For Year 0, there is no operational energy consumption. GHG emissions are calculated by multiplying lifecycle emissions per unit of vehicle capital by the quantity of new vehicle capital.

- For Years 1 through N, vehicle energy use and GHG emissions are the total of:
    - Energy/GHG impacts of vehicle operation, calculated by multiplying impacts per VKT by projected annual modal VKTs;
    - Energy/GHG impacts of vehicle maintenance/repair, calculated by multiplying impacts per VKT by projected annual modal VKTs; and
    - GHG impacts of new/replacement vehicle capital, calculated by multiplying lifecycle emissions per unit of vehicle capital by the quantity of new vehicle capital.

- For Year 2 through Year N, efficiency gains in vehicle fuel economy/power consumption rate and reduction in power emission factor are incorporated by multiplying energy consumptions/GHG emissions from vehicle operation by $(1 - \textit{average annual reduction rate})^{n-1}$.

Similarly, for each year, the infrastructure energy/GHG impacts are obtained by adding together the impacts of each type of infrastructure (some infrastructures are shared by multiple modes), which are calculated as below.

- For Year 0, there is no operational energy consumption. GHG emissions are calculated by multiplying the lifecycle emissions per unit of infrastructure capital by the quantity of new infrastructure capital.

- For Years 1 through N, infrastructure energy use and GHG emissions are the total of:
    - Energy/GHG impacts of infrastructure operation/maintenance, calculated by multiplying average annual impacts per infrastructure unit by the quantity of infrastructure in use; and
    - GHG impacts of new/replacement infrastructure, calculated by multiplying lifecycle emissions per unit of infrastructure by the quantity of new infrastructure units.

- For Year 2 through Year N, reduction in power emission factor is incorporated by multiplying GHG emissions from infrastructure operation by *(1 – average annual reduction rate)*$^{n-1}$.

APPENDIX 4: CONTENTS OF THE SPREADSHEET TOOL

Sheet 1: Title and Index

Lifecycle Assessment of Urban Transport Systems in China

Updated May 10, 2011

This tool estimates lifecycle GHG (in CO2e) emissions and major operational energy (power, gasoline, diesel and CNG) consumptions of a user-specified urban transport system in China. The lifecycle components considered include vehicle production, operation and maintenance, fuel production and distribution, and infrastructure material production, construction, operation and maintenance. It is capable of analyzing the emissions from a variety of vehicle technologies, including gasoline ICE, gasoline-electric hybrid, diesel ICE, diesel-electric hybrid, CNG ICE, and electric motors. The output of the tool includes GHG emissions and operational energy consumptions by year during a study period up to 30 years.

INDEX	
Input	User input
A	Data on GHG emission factors of fuel and power
B	Data on use-phrase energy consumption rates
C	Data on GHG emissions of capital production and processes other than vehicle operation
Results	Results
[Scenario Name]	User input and results

Sheet 2: Input (partial images shown)

Instructions: 1. enter data in the grids highlighted in yellow
2. click "Run Program" at the bottom of the page
3. go to the Results sheet to view results

SECTION ONE: PLAN/PROJECT DESCRIPTION

Study Period (year) 30 Note: choose a study period up to 30 years

CAPITAL INVESTMENT - VEHICLE Note: vehicle capital ir

Type	Unit	Quantity
Heavy rail	Heavy rail car	
Light rail	Light rail car	
Diesel bus	12 m bus	
CNG bus	12 m bus	
Hybrid bus (diesel-electric)	12 m bus	
Gasoline car	1.6L sedan	
Diesel car	1.6L sedan	
Hybrid car (gasoline-electric)	1.6L sedan	
Motorcycle	100cc motorcycle	
Electric bicycle	Electric bicycle	
Bicycle	Bicycle	

CAPITAL INVENTORY AND INVESTMENT - INFRASTRUCTURE Note: existi

Type			Unit	Existing	New
Right of Way	At-grade	Expressways	Lane-km (3.75 m wide)		
		Major arterials	Lane-km (3.75 m wide)		
		Minor arterials	Lane-km (3.5 m wide)		

SECTION TWO: FORECASTS

(Enter data for the study period specified above only)

TRAFFIC FORECASTS: AGGREGATE VKT (VEHICLE-KM TRAVELED) BY VEHICLE TYPE (Note: annua

Type	Unit	Year 1	Year 2	Year 3
Heavy rail	Heavy rail car			
Light rail	Light rail car			
Diesel bus	12 m bus			
CNG bus	12 m bus			
Hybrid bus	12 m bus			
Gasoline car	1.6L sedan			
Diesel car	1.6L sedan			
Hybrid car	1.6L sedan			
Motorcycle	100cc motorcycle			
Electric bicycle	Electric bicycle			
Bicycle	Bicycle			

FORECASTS OF NEW VEHICLE CAPITAL (REPLACEMENT PLUS ADDITION) (default=0)

Type	Unit	Year 1	Year 2	Year 3
Heavy rail	Heavy rail car			
Light rail	Light rail car			
Diesel bus	12 m bus			
CNG bus	12 m bus			
Hybrid bus	12 m bus			
Gasoline car	1.6L sedan			
Diesel car	1.6L sedan			
Hybrid car	1.6L sedan			
Motorcycle	100cc motorcycle			
Electric bicycle	Electric bicycle			
Bicycle	Bicycle			

FORECASTS OF NEW INFRASTRUCTURE CAPITAL (REPLACEMENT PLUS ADDITION) (default=0)

Type			Unit	Year 1	Year 2	Year 3
Right of Way	At-grade	Expressways	Lane-km (3.75 m wide)			
		Major arterials	Lane-km (3.75 m wide)			
		Minor arterials	Lane-km (3.5 m wide)			
		Collectors	Lane-km (3.5 m wide)			
		Bicycle lanes	Lane-km (3 m wide)			

EXPECTED CARBON EMISSION REDUCTION OF ENERGY CONSUMPTION		Note: enter "x" if x% a
Energy Type	**Average Annual % Decrease in Emission Factors (default=0)**	
Electricity		Scenarios in Ou et al

EXPECTED GAINS IN VEHICLE ENERGY EFFICIENCY		Note: enter "x" if x% a
Vehicle Type	**Average Annual % Decrease in Energy Consumption per VKT (default=0)**	
Heavy rail		
Light rail		
Diesel bus		
CNG bus		
Hybrid bus		
Gasoline car		
Diesel car		
Hybrid car		
Motorcycle		
Electric bicycle		

Run Program

Sheet 3: Data A – GHG emission factors of fuel and power (partial image shown)

GHG emission factors of fuel and power					
ELECTRICITY					
Average EF	1.072	kg/kWh			
FOSSIL FUEL					
Fuel Type	**CO2 (kg/L)**			**CH4 (kg/L)**	
	Direct	*Indirect*	*Total*	*Direct*	*Indirect*
Gasoline					
Diesel					
CNG					

Sheet 4: Data B – Use-phase energy consumption rates (partial image shown)

Use-phase energy consumption rates

VEHICLE FUEL ECONOMY/POWER CONSUMPTION		
Vehicle Type	**Value**	**Unit**
Heavy Rail	6	kWh/VKT
Light Rail	4	kWh/VKT
Diesel Bus	0.4	L diesel/VKT
CNG Bus	345	L CNG/VKT
Hybrid Bus	0.31	L diesel/VKT
Gasoline Car	0.085	L gas/VKT
Diesel Car	0.068	L diesel/VKT
Hybrid Car	0.05	L gas/VKT
Motorcycle	0.03	L gas/VKT
Electric Bicycle	1.5	kWh/VKT
Bicycle	0	n/a

POWER CONSUMPTION OF INFRASTRUCTURE OPERATION AND MAINTENANCE			
Infrastructure Type			**Power Consumption (kWh per unit infrastructure-yr)**
Right of Way	At-grade	Expressways	15200
		Major arterials	15200
		Minor arterials	10400
		Collectors	8800
		Bicycle lanes	8800
		Rail ROW	0
	Elevated	Expressways	15200
		Rail ROW	0
	Underground	Expressways	30400
		Rail ROW	0
Stations	At-grade	BRT	2700

Sheet 5: Data C – GHG emissions of capital production and processes other than vehicle operation (partial image shown)

GHG emissions of capital production & processes other than vehicle operation

VEHICLE CAPITAL (kg per unit)

Vehicle Type	CO_2	CH_4	N_2O	CO2e
Heavy rail				230000
Light rail				355000
Diesel bus				129000
CNG bus				129000
Hybrid bus				129000
Gasoline car				10000
Diesel car				10000
Hybrid car				10000
Motorcycle				1000
Electric bicycle				740
Bicycle				100

VEHICLE MAINTENANCE, REPAIR, AND PART REPLACEMENT (kg per VKT)

Vehicle Type	CO_2	CH_4	N_2O	CO2e
Heavy rail				0
Light rail				0
Diesel bus				0.03
CNG bus				0.03
Hybrid bus				0.03
Gasoline car				0.015
Diesel car				0.015
Hybrid car				0.015
Motorcycle				0.005
Electric bicycle				0.002
Bicycle				0.001

INFRASTRUCTURE CAPITAL (kg per unit)

Infrastructure Type			CO_2	CH_4	N_2O	CO2e
Right of Way	At-grade	Expressways				553000

Sheet 6: Results (partial image shown)

Results

Study Period (yr)	30

	Operational Energy Consumption				Lifecycle GHG Emissions			
	Electricity (kWh)	Gasoline (L)	Diesel (L)	CNG (L)	CO_2 (kg)	CH_4 (kg)	N_2O (kg)	CO_2e (kg)
Year 0	0	0	0	0	0	0	0	0
Year 1	0	0	0	0	0	0	0	0
Year 2	0	0	0	0	0	0	0	0
Year 3	0	0	0	0	0	0	0	0
Year 4	0	0	0	0	0	0	0	0
Year 5	0	0	0	0	0	0	0	0
Year 6	0	0	0	0	0	0	0	0
Year 7	0	0	0	0	0	0	0	0
Year 8	0	0	0	0	0	0	0	0
Year 9	0	0	0	0	0	0	0	0
Year 10	0	0	0	0	0	0	0	0
Year 11	0	0	0	0	0	0	0	0
Year 12	0	0	0	0	0	0	0	0
Year 13	0	0	0	0	0	0	0	0
Year 14	0	0	0	0	0	0	0	0
Year 15	0	0	0	0	0	0	0	0
Year 16	0	0	0	0	0	0	0	0
Year 17	0	0	0	0	0	0	0	0
Year 18	0	0	0	0	0	0	0	0
Year 19	0	0	0	0	0	0	0	0
Year 20	0	0	0	0	0	0	0	0
Year 21	0	0	0	0	0	0	0	0
Year 22	0	0	0	0	0	0	0	0
Year 23	0	0	0	0	0	0	0	0
Year 24	0	0	0	0	0	0	0	0
Year 25	0	0	0	0	0	0	0	0
Year 26	0	0	0	0	0	0	0	0
Year 27	0	0	0	0	0	0	0	0
Year 28	0	0	0	0	0	0	0	0
Year 29	0	0	0	0	0	0	0	0
Year 30	0	0	0	0	0	0	0	0
TOTAL	0	0	0	0	0	0	0	0

APPENDIX 5: DATA EXPLANATION (INFRASTRUCTURE PART) BY THE TSINGHUA TEAM

数据说明

1．材料生产能耗和排放

材料生产能耗和排放数据包括钢材，水泥，混凝土、沥青的生产周期能耗和排放的数据。

数据来源：

《基于LCA
的建材生产能耗及污染物排放清单分析》，王婧，张旭，黄志甲，《环境科学研究》2007年第20卷第6期

《建筑生命周期能源消耗及其环境影响研究》，仲平，四川大学硕士论文，2005

沥青排放数据国内目前没有相关数据，此处采用原油提炼排放与热拌沥青混合料生产过程排放之和。数据来自《炼油厂CO2排放现状及回收应用分析》，《安全．健康和环境》，2007年第1期

2．轨道交通建设阶段能耗和排放

计算中将建设过程分为准备阶段和建设阶段，准备阶段能耗与排放为材料生产的排放与能耗，建设阶段能耗与排放为施工过程中机械耗电的能耗与排放。根据实际案例数据计算材料使用量，按照机械费用的1%计算施工过程耗电量。

区间部分为地铁区间工程建设阶段材料用量（不包括钢轨铺设用材），能源消耗及排放，包括高架区间工程，暗挖区间工程，盾构区间工程。并以北京市地铁4号线铁轨铺设用材做参考数据

数据来源：

北京造价网http://www.bjzj.net/BJCostWeb/Default.aspx

案例一：北京地铁高架桥区间，五环路以外

案例二：北京地铁盾构区间，二环路以内

案例三：北京地铁暗挖区间，三环路以内

北京京港地铁公司（四号线）实际数据

车站（车辆段）部分为地铁车站工程建设阶段材料用量，能源消耗及排放，包括地铁高架车站，地铁暗挖车站，地铁明挖车站和暗挖盖挖结合地铁车站。

数据来源：

北京造价网http://www.bjzj.net/BJCostWeb/Default.aspx

案例一：地铁高架车站，五环路以外

案例二：地铁暗挖车站，三环路内

案例三：地铁明挖、两层岛式车站，二环路以外

案例四：暗挖、盖挖相结合、三层岛式地铁车站

北京京港地铁公司（四号线）实际数据

以上案例详见附录1、2。

数据单位：

区间部分按照单位长度（lane-km）计算，车站部分按照单位面积（m^2）计算。

3．路面交通建设阶段能耗和排放

计算中将建设过程分为准备阶段和建设阶段，准备阶段能耗与排放为材料生产的排放与能耗，建设阶段能耗与排放为施工过程中机械耗电的能耗与排放。根据实际案例数据计算材料使用量，按照机械费用的1%计算施工过程耗电量。

数据来源：

道路结构形式与车道宽度以根据我国《城市道路设计规范》CJJ37-90以及北京市路建设具体案例确定。BRT车站尺寸根据《城市道路设计规范》CJJ37-90港湾式停靠站标准确定。材料用量以及机械费用根据《北京市建设工程预算定额》标准参考实际案例计算。

北京造价网http://www.bjzj.net/BJCostWeb/Default.aspx

案例一：无辅路道路工程，五环路以外

案例二：有辅路道路工程，三环路以内

案例三：立交桥工程（T型梁，箱梁），四环路以外

以上案例详见附录3。

数据单位：

道路按照单位道路长度（km/lane）计算。BRT车站按照标致车站个数（个）计算。

4.停车场建设阶段能耗和排放

计算中将建设过程分为准备阶段和建设阶段，准备阶段能耗与排放为材料生产的排放与能耗，建设阶段能耗与排放为施工过程中机械耗电的能耗与排放。根据实际案例数据计算材料使用量，按照机械费用的1%计算施工过程耗电量。

数据来源：

标准停车位面积根据《停车场规划设计规则（试行）》确定，材料使用量以及机械费用根据《北京市建设工程预算定额》标准参考实际案例计算。

案例一：地上停车楼工程

案例二：地下停车库工程

以上案例详见附录4。

数据单位：

停车场按照标准停车位个数（个）计算。

5.轨道交通运营维护能耗及排放

轨道交通运营维护能耗及排放按照京港地铁公司（四号线）实际运营数据计算。其中动力电量轨道车辆运行外的电力消耗，用于计算车站耗电量。牵引电量为轨道车辆运行所需电量，用于计算区间（轨道）耗电量。6月-9月，由于是制冷季的缘故，因此车站动照电量将为非制冷季的2倍，牵引约为1.3倍。车辆段电力消耗约为普通车站的2倍。

数据来源：

北京京港地铁公司（四号线）实际运营数据。

用电量（2010年5月份,不含商业用电）：

分类	动力电量	牵引电量	正线总电量
用电量（度）	3,026,938	5,139,047	8,165,985

数据单位：

区间（轨道）部分按照单位长度（km）计算，能耗单位为MJ/km/y，排放单位为kg/km/y。

车站部分按照站台个数（个）计算，能耗单位为MJ/个/y，排放单位为kg/个/y。

6.路面交通运营维护能耗及排放

路面交通运营维护能耗及排放主要计算照明耗电作为运营维护耗能指标，排放数据根据我国采用火力燃煤发电生产相应电量的排放。

道路运营维护阶段能耗（排放） = 单位时间每公里单车道照明能耗（排放） × 照明时间（小时/年）

单位时间每公里单车道照明能耗（排放） = 照明功率密度值（LPD） × 单车道宽 × 1公里

数据来源：

《城市道路照明设计标准》CJ45-2006

中国照明网 http://www.lightingchina.com/science/kp_zhishi/KP_zmln.htm

数据单位：

道路运营维护阶段按照道路单位长度计算，能耗单位MJ/公里单车道/y，排放单位kg/公里单车道/y。

7.停车场运营维护能耗及排放

停车场运营维护能耗及排放考虑运营中耗电量，即照明耗电量。停车位标准面积根据《停车场规划设计规则（试行）》确定。地下停车照明为24小时不间断长明灯，地面停车场及停车楼照明均取为12h/天。照明功率密度值（LPD）参考道路照明设计准则，取自行车道标准，选取5W/m^2。计算时考虑火力燃煤发电方式下的排放数据。

数据来源：

《城市道路照明设计标准》CJ45-2006

《停车场规划设计规则（试行）》

中国照明网 http://www.lightingchina.com/science/kp_zhishi/KP_zmln.htm

数据单位：

停车场运营维护阶段按照标准停车位个数计算，能耗单位为MJ/个/y，排放单位为kg/个/y.

APPENDIX 6: FINAL REPORT BY THE CHINA ACADEMY OF TRANSPORTATION SCIENCES TEAM

基于全生命周期的不同交通方式

的能源消耗与碳排放研究

交通运输部科学研究院
城市交通研究中心
二〇一〇年九月

•

• 第一章 研究背景及意义

改革开放以来，我国城市化进程不断加快，社会经济稳步高速发展，交通运输需求不断上升，交通发展与能源紧缺、环境污染的矛盾日益突出。在交通运输活动中，城市是运输网络的重要节点和中心，城市交通的快速发展，同时也加剧了交通能耗和环境排放，并已逐渐成为能源消耗和温室气体排放的大户。据预测，到2030年，中国城市交通的能源消费量将达到6.5亿吨标煤，将是2005年的5倍。在当今应对全球气候变化的大背景下，为落实资源节约的基本国策，实现国家2020年的碳减排目标，加快“资源节约、环境友好型”交通建设，迫切要求切实落实城市公共交通优先发展战略，形成低碳高效的城市综合运输体系，以提高城市交通的能源效率，有效减缓二氧化碳排放。

在多数交通能源与排放的研究中，城市公共交通被普遍认为是单位能效最高和二氧化碳排放强度最低的交通方式，但事实上始终缺乏具有足够说服力的数据来证明，主要原因是国内基于全生命周期角度考虑的研究为数不多，尤其是结合我国以煤炭为主的能源结构，城市公共交通，尤其是轨道交通的单位周转量的碳排放是否依然是最低目前尚不明确。同时，由于国内的统计基础薄弱，统计指标不完善，大大增加了开展基于全生命周期研究的难度。截至目前，国内已存在的相关研究成果主要来源于能源基金会、中国汽车技术研

究中心、中国石油规划研究院等研究单位，但多数研究都是基于燃料（石油基、煤基、生物质基等）循环的全生命周期的能源消耗与碳排放研究，基于全生命周期的不同交通方式的能源消耗与碳排放研究，国内至今尚未有系统的研究成果。因此，现阶段开展本研究具有很强的必要性和重要的现实意义。

• 第二章 研究范围

本课题的研究范围主要包括城市轨道（主要是地铁）、公共汽车（汽油、柴油、CNG、LPG、电力）、小汽车、出租车、电动自行车、自行车等。为进一步开展深入研究，本研究以城市交通中不同交通工具的车辆、燃料制造和运营阶段为主，开展不同交通方式的单位能耗和单位排放研究。

项目调研重点选择北京作为主要案例城市开展了小样本的抽样调查。

• 第三章 研究方法

• 3.1 车辆制造阶段

车辆制造阶段的能耗数据非常难于获取，因此我们采取了现有数据调研、专家咨询，加上类比计算的方式。

⑴ 私人小汽车制造阶段能耗

每辆车约627千克标煤/车；

计算方法：根据文献中列出的小汽车制能耗取平均值[8]，即

$$EN_{private} = \frac{\sum_{j=0,1...i}^{i} e_j}{i}$$

⑵ 公交车辆制造阶段能耗

计算方法：根据其车重与小汽车的比值，进行折算，即

$$EN_{bus} = \frac{Weight_{bus} * EN_{private}}{Weight_{private}}$$

（注 1： 此处公交车辆与私人小汽车车重也为我们取样的平均值；

2： BRT车辆跟一般公交车没有区别，不按照燃料类型进行划分）。

⑶ 二氧化碳排放

计算方法：用⑵中的单车能耗乘以二氧化碳排放因子，即

$$EM_i = EN_i * factor_{em}$$

• 3.2 车辆运营阶段

◆ 公交和轨道交通车辆

---

[8] 参考文献 [illegible] 2007（11）：21-23

通过开展城市公交企业调研，调查公交、轨道交通车辆的年运营里程、能源消费量，计算得出不同燃料类型城市公交车辆的单位能耗和单位排放。

◆ 社会车辆

以现有研究和文献资料为基础，结合专家咨询，测算得到不同燃料类型社会车辆的单位能耗和单位排放。

• 3.3 燃料生产阶段

⑴ WTP阶段（从油井到油箱）能耗

汽油车能耗为226664 Btu/MMBtu、柴油车能耗为206851 Btu/MMBtu[9]。

⑵ 将 ⑴ 中能耗折算成标准煤

计算方法: 1)能耗直接乘以转换系数（Conversion factor），即

$$E_2 = E_1 * \mathrm{Conversionfactor}$$

⑶ WTP阶段碳排放

计算方法：⑵ 能耗乘以碳排放系数（Carbon emission factors），即

$$EM = E_2 * \mathrm{Carbonemissionfactor}$$

（附：carbon emission factors）

• 第四章 研究内容

• 4.1 车辆制造阶段能耗及碳排放

因为车辆制造涉及发动机、底盘、车身三部分多个零部件的装配，包括冲压、焊装、涂装和总装四大流程。资料显示，汽车行业中，除整车制造企业外，毛坯和零部件制造企业通常单位产值的能耗较高，且不同地区的汽车企业在能耗方面存在差异。故选取八个汽车企业的私人小汽车制造能耗，并取其能耗平均值627千克标准煤/车。因车型接近，所以出租车制造阶段的能耗与排放数值应与小汽车接近。

对于公交车辆，根据其车重与小汽车的对比关系，大致估算其制造阶段能耗平均值分别为5076千克标准煤/车。

目前国内BRT车辆并没有采用特殊公交车辆，只是在路权优先上给予更多倾斜，故而可将其与公交车辆合并。

事实上，在国内汽车制造企业，并没有对车辆制造全过程的排放进行系统统计。且某些流程数据涉及企业商业机密，导致车辆制造阶段的能耗数据非常难于获取，我们通过对专家的调查和文献的学习，掌握到以上数据。

[9] 数据来源：中国[illegible]2005年数据

- ## 4.2 车辆运营阶段能耗及碳排放

车辆运营阶段的能耗及排放比较复杂，因为涉及工况多、路况各异、不同的司机在驾驶水平存在差异导致能耗和碳排放相应差别。

目前的城市公交数据主要依靠以往统计和现阶段公交企业调查相结合获得。轨道交通的数据主要来自于北京地铁企业调查。

由于统计数据缺失，全国公交车辆的能耗总量数据较难获取，按照研究方法分类，根据对北京市公交企业的调研，并以北京市的单位能耗数据来代表全国的数据，数据如下：

运营阶段，公交车燃油经济性：汽油28.754 L/100km，柴油27.142 L/100km，CNG 40.235 L/100km，混合动力22 L/100km。

BRT柴油车辆的燃油经济性：柴油70L/100km[10]。

与城市公交车辆能耗类似，全国轨道交通车辆的能耗数据，因为统计数据缺失，总量较难获取。根据对北京市的调查，2008年北京市轨道交通年耗电量26824.27万千瓦时，年投入行驶14658万车公里，由此得到每车公里的能耗值为1.83千瓦时。

社会车辆中，私人小汽车的燃油经济性为9.3 L/100km。混合动力小汽车的燃油经济性为3.5 L/100km。摩托车的燃油经济性为2.7 L/100km[11]。

国内几乎没有柴油小汽车，因此无数据可用。

- ## 4.3 燃料生产阶段能源消耗与碳排放

- ### 4.3.1 汽油、柴油生产阶段能源消耗与碳排放

⑴汽、柴油生产阶段能耗

针对汽油、柴油这两种常用石油车用燃料进行燃料能源评价，并将汽油、柴油作为车用替代燃料能源评价的比较基准，力求通过数据研究，综合评价各种石油替代燃料，采用美国能源部Argonne国家试验室开发的GREET模型，对各种燃料进行全生命周期评价。其基本思路是在全生命周期中生产、运输、储存等不同环节，根据不同的能源和动力系统、不同原料的含硫、含碳量、各环节的损耗率、以及各环节用能量效率表征的技术水平，全部追溯到一次能量消耗和排放，最终计算WTP过程中总排放和总能效指标。

汽油和柴油都属于石油基燃料，它们都是由石油一步一步开采加工得到。按照研究思路，需要分析石油燃料能源效率。能源效率概念为从能源开采到终端利用各个环节，所得到的有效能源量与实际消耗的能源量之比。从能源消费角度，能源效率是指为终端用户提供的能源服务与所消耗的能源量之比。石油燃料能量效率的分析主要包括原油开采效率、标准炼厂全厂能耗计算、设计标准炼厂的总能量输入与输出情况、各种产品的能量分配和各种油品能量效率五个方面。

◆ 原油开采效率

---

[10] 数据来源：中国交通：不同交通方式的能源消耗与排放报告，第51页

[11] 数据来源：中国城市交通中长期能源需求与碳排放情景，国家发改委能源所，2009

能源效率分为开采效率或采收率、用从一定的能源储量中采出来的产量热值与储量热值之比来衡量。研究边界定为油田井口，因此，原油开采能量效率计算包括原油开采损耗、原油集输到集输站、以及各装置公用工程消耗的影响。

能源加工与转化效率是指煤、石油、天然气等精选与炼制，以及炼焦、发电、产热、汽化、液化等一次能源转换成为二次能源的过程，加工转化效率指能源的产量与加工转换时投入的能源量之比，其差额为加工转换中的损失和消费的能源。贮运效率用能的输送、分配和贮存过程中的损失能量，一般不包括自身消耗的能源。

原油开采效率=原油产量热值/（原油产量热值+原油采出损耗+采油能耗+原油集输能耗）

我国油田开采损失率约1.5%，而美国为0.3%，俄罗斯为0.6%，考虑到我国油田开采损失率中有少量油田自用。

◆ 标准炼厂全厂能耗计算

炼油厂根据加工原油品质差异，以及产品结构和产品质量要求不同，各个炼油厂加工工艺流程有较大差别，为了比较不同炼厂之间的加工能量，一般用能量因数，将各工艺相对于常压蒸馏的加工系数进行加和，得到单位因素能耗指标。研究设计了生产清洁油品的标准流程，取国内各装置平均消耗指标，作为油品能量效率的比较基准数据。再根据设计炼厂流程及各种消耗情况，可以得出设计装置能耗。

为了比较不同加工流程炼厂的能耗水平，石油化工行业规定将各二次加工工艺能量都统一折算成常压蒸馏工艺消耗的当量值，定义各加工工艺的能量因子Ki，其意义为在二次加工装置加工一个单位的进料量，相当于常压蒸馏加工一个单位原油的能量消耗倍数。则Ki与各装置的对比处理量的乘积，得到各装置的能量因数。各装置能量因数的合计为全厂能量因数。最终通过单位能量因数的能耗值比较不同加工流程炼厂的能耗水平。设计炼厂能耗包括全厂能耗及公用工程能耗（如下表1），计算得出该工业流程条件下，炼油的单位能量因子能耗值为11.47 Kgtoe/t。

表1 1000万吨标准炼厂全厂能耗指标情况

全厂能耗计算表	消耗量	折能指标	能耗
燃料油	29.63 t/h	41868 MJ/t	1240548.8 MJ/h
燃料气	34.795 t/h	33494 MJ/t	1165423.7 MJ/h
电	74680 kW	12.56 MJ/度	937980.8 MJ/h
水	1667 t/h	7.54 MJ/t	12569.2 MJ/h
催化烧焦	7.21 t/h	41868 MJ/t	301868.3 MJ/h
能耗合计			3658390.8 MJ/h
吨加工原油能耗			2883.7 MJ/t 原油
吨加工原油能耗			68.89 千克标油/t 原油
全厂总输入工艺能量			2.774e+13 BTU
单位因素能耗			480.06 MJ/t 因素
单位因素能耗			11.47 千克标油/t 因素

注：单位因素能耗=单位能耗/全厂能量因素

◆ 设计标准炼厂的总能量输入与输出情况

为计算炼厂的总能量输入与输出，计算中取各种燃料的低热值，再根据各种原料标准低热值和炼厂产品的产率情况，计算出炼厂总输出能量，如下表2。

表2 设计标准炼厂输入与输出情况

产品名称	规格	产量 吨	质量分数	折能量 BTU
LPG		436273	4.362%	2.02735E+14
石脑油		252069	2.520%	1.38349E+13
苯		111437	1.114%	4.59408E+13
混二甲苯		387198	3.871%	1.59625E+14
汽油		1878521	18.782%	7.74435E+14
煤油	Jet fuel	150000	1.500%	6.05851E+13
柴油	S<0.2%	3737973	37.372%	1.51072E+15
柴油	S<30ppm	350000	3.499%	1.41454E+14
柴油	S<500ppm	1633096	16.328%	6.60025E+14
燃料油		32206	0.322%	1.2421E+13
石油焦		577052	5.769%	1.18484E+13
输出能量合计		10001914		3.59363E+15
原油输入能量		10001961	100.000%	4.0633E+15
加工工艺输入总能量				2.77E+13

根据上表计算炼厂总能量效率如下

$$全厂总效率E_{汽油} = \frac{产品总热值}{原油总热量+吨加工原油加工能耗}$$

$$= \frac{(3.59363E15)}{(4.0633E15)+(2.77E13)} = 0.8791$$

◆ 各种产品的能量分配

按照工艺流程将针对各种主要油品计算分配系数，分配原则如下：

第一步：计算各产品的能耗

①

根据各工艺不同馏份的收率，计算汽油、柴油、LPG、煤油、石脑油等产品的在各装置分摊的能耗值E_{ij};

②

根据二次加工装置的进料量和不同馏份收率计算汽油、柴油、LPG、煤油、石脑油等产品的中间加工分摊的能耗值Z_{ij}；

③

按照全流程总收率分摊公用工程，包括制氢、水、电、汽、空分等生产时的能耗G_{ij}；

第二步：加合计算产品①、②、③三部分总能耗；

I种产品的工艺计算总能耗 = $E_{ij} + Z_{ij} + G_{ij}$

第三步：计算得到各产品能耗占全厂总能耗的份额，得能量分配系数W_i。

根据炼厂各加工工艺产品收率，计算主要产品的能量消耗如表3所示。LPG向装置提供制氢原料，因此为负值。

表3 炼厂产品能量消耗 MJ/吨原油

产品名称	装置单位能耗	中间装置分摊	制氢及公用工程分摊	产品加工能耗合计	工艺分配系
LPG	85.22	34.01	-59.92	59.31	2.06
石脑油	12.63	8.81	35.06	56.50	1.96
汽油	123.29	141.65	296.60	561.53	19.47
柴油	486.28	260.83	740.02	1487.13	51.56
煤油	78.84	25.58	70.12	174.54	6.05
五大主产品能耗合计				2339.00	81.10
全厂总能耗				2884.00	100%

◆ 各种油品能量效率

根据设计炼厂的总能量效率，计算汽油、柴油、LPG
等主要产品的能量效率。炼厂滴i产品的能量效率定义为：

$$\eta_i = E_i/(E_i + E_p)$$

其中，E_i 为产品所含热值，各种能量均取产品低热值计算，

E_p 为加工产品所消耗的能量，水电汽折能指标根据国家标准计算。

计算中引入产品相对能量强度参数如下：

$$X_i = W_i/\phi_i$$

其中，W_i 为工艺能量分配份额，ϕ_i 为产品质量份额。

根据这两个公式可以推导出下式：

$$\eta_i = \frac{1}{1 + X_i((1/\eta_{总}) - 1)}$$

将炼厂总效率87.91%代入上式，根据上式计算主要石化产品能量效率结果如表4所示
。

表4 炼厂产品能量分配系数计算

产品名称	工艺分配系数	产品质量分数	能量分配强度系数	能量效率
LPG	0.0	0.1	0.5	93.9
汽油	0.2	0.2	1.1	87.1

柴油	0.5	0.6	1.0	88.4
五大主产品能耗占全厂	0.8	0.8	1.0	87.9

考虑到由于环保要求提高和技术进步因素，使不同炼厂平均能耗情况有较大差异，生产清洁燃料会使能耗和物耗增加，我们比较了所设计的标准炼厂与国内实际炼厂的差异，目前国内典型炼厂的能耗情况如表5所示。

表5 国内炼厂能耗平均水平

炼厂类型	单位能耗	能量因素	能量因素能耗
	KGBO/吨加工量		KGBO/T 原油.因素
燃料润滑油型	54.47	4.142	13.151
燃料型1	74.11	5.5644	13.107
燃料型2	67.61	5.187	13.033
国内平均水平	65.3	4.963	13.15
国内先进水平	64.24	5.422	11.84
设计标准			11.47

从上表可以看出，设计炼厂的工艺能耗指标优于目前国内实际水平，考虑到多种因素的不同影响，包括实际炼厂平均操作水平低于设计炼厂、加工高硫油使炼厂能耗增加、汽油标准提高使炼厂能源增加等多种因素，修正不同时期各种石油基燃料的能量效率如表6所示。

表6 不同时期各种石油基燃料能量效率估算

	汽油	欧II汽油	欧III汽油	柴油	低硫柴油	LPG
现状	0.87			0.88		0.93
近期		0.85			0.87	0.93
远期			0.84		0.86	0.92

通过以上一系列的步骤，最终可以采用GREET模型计算石油基燃料生产消耗能量如表7所示。

表7 单位石油基燃料生产消耗总能量 Btu/mmBtu

	原油生产	汽油生产	柴油生产	LPG生产
原油	246	0	0	0
渣油	246	62988	57491	31733
柴油	3684	0	0	0
汽油	491	0	0	0
天然气	15228	0	0	0
煤	0	0	0	0

电	4667	38851	35455	19570
原料损失	29	0	0	0
炼气厂		47607	43445	23981
油田伴生气	16,800			
总能量	35185	226664	206851	114176
其中化石燃料	49,955	376,793	205,523	1,004,780
石油	8,016	196,112	106,970	522,967

⑵ WTP阶段

根据调查，WTP阶段，汽油车能耗为226664Btu/MMBtu、柴油车能耗为206851Btu/MMBtu[12]。

- ## 4.3.2 电力生产过程能源消耗与碳排放

⑴ 电力生产过程能源消耗

根据发电厂燃料品种和电厂能量效率，计算电力生产的效率和排放情况。根据中国热电厂生产水平和排放情况，对GREET模型中的计算基准进行适当修正。

根据2005年中国统计年鉴，国内发电效率约为39.3％。发电厂用锅炉以粉煤炉及链条炉为主，大型发电厂一般采用粉煤炉，中小型发电厂采用链条炉，目前发电厂很少采用循环流化床锅炉和燃气轮机。石油化工企业自备热电厂用锅炉以循环流化床锅炉为主。

2004年，中国全年发电量达到21870亿千瓦时，比上年增长14.8%。其中，水电发电量为3280亿千瓦时，占总发电量的比重为15.06％，同比增长16.6%，主要得益于三峡等大型水电机组陆续投产发电；火电发电量为18073亿千瓦时，占82.98%，同比增长14.5%，火电占绝对主导地位；核电发电量稳步增长，全年发电量501亿千瓦时，占2.30％，同比增长14.1%。表8是2004年来中国电力生产情况及近几年生产发展变化情况。

表8 2004年中国电力生产情况

项目	单位	2004年
发电量	亿千瓦时	21870
水电	亿千瓦时	3280
火电	亿千瓦时	18073
核电	亿千瓦时	501
供电标准煤耗	克/千瓦时	379
发电利用小时	小时	5460
水电	小时	3374
火电	小时	5988

资料显示，

12 数据来源 中国[illegible]2005年数据

电力的发电标准煤耗：水电16gce/kwh，火电400gce/kwh；

电力的供电标准煤耗是379gce/kwh[13]。

• 第五章 存在的主要问题

因为中国城市交通部门的能耗和碳排放数据统计基础十分薄弱，且经历大部制改革后，历史数据的统计数据口径方面存在变化，故而我们主要还是采取“核实历史数据+样本调查+专家咨询+类比计算”的方式。

（1）车辆制造数据的问题

由于企业管理理念的原因，中国大部分汽车制造企业并未统计车辆制造全过程的能耗，加上涉及企业商业机密。目前无论是官方的统计资料，还是企业的统计报表中，车辆制造阶段的能耗数据普遍缺失。

本报告采用历史文献加专家咨询的方式获得的数据，车重和能耗都是取的平均值。相应的，碳排放数据也存在这个问题。

（2）调查数据的问题

由于历史数据缺失，本研究中的很多数据来自于调查数据。例如轨道交通车辆运营阶段的数据来自于北京市的调查数据。目前中国的轨道交通发展迅速，虽具有较强的代表性，数据质量在深度和广度方面还有待进一步提高。

（3）其他温室气体排放

至今为止，国内对交通领域内尚没有开展除CO_2以外的温室气体如CH_4、N_2O和CO2e等的研究，导致这些数据无法收集。

• 附录

附录：数据说明

一、 数据表结构

1、基本因子

2、车辆制造阶段详表

3、道路施工阶段详表

4、燃料详表

5、车辆运营阶段详表

6、公共交通能源消耗情况表

二、 数据说明

1. 基本因子

[13] 数据来源：[illegible]，水力发电[illegible]，2004年[illegible]月

（1） 能耗因子

能耗基本因子包括吨钢综合能耗因子和水泥产品综合能耗因子。
（数据来源：《中国能源统计年鉴2007》）。
（2） 碳排放因子

(数据来源：IPCC 2006报告)。

2． 车辆制造阶段详表

车辆制造阶段的能耗数据非常难于获取，因此我们采取了现有数据调研、专家咨询，加上类比计算的方式：

1） 私人小汽车制造阶段能耗

每辆车约627千克标煤/车；
计算方法：根据文献中列出的小汽车制能耗取平均值，即

$$EN_{private} = \frac{\sum_{j=0,1...i}^{i} e_j}{i}$$

(参考文献：田文彪，魏明，尹娟，宋衍国，汽车制造企业能耗分析及节能新技术，节能，2007（11）：21-23 ；）

2） 公共汽车制造阶段能耗

计算方法：根据其车重与小汽车的比值，进行折算，即

$$EN_{bus} = \frac{Weight_{bus} * EN_{private}}{Weight_{private}}$$

（注 1： 此处公共汽车与私人小汽车车重也为我们取样的平均值；
2： BRT车辆跟一般公交车没有区别，不按照燃料类型进行划分）。

3） 碳排放

计算方法：用（2）中的单车能耗乘以排放因子，即

$$EM_i = EN_i * factor_{em}$$

3． 燃料生产阶段

1) WTP阶段能耗
汽油车能耗为226664Btu/MMBtu、柴油车能耗为206851Btu/MMBtu。
（数据来源：中国车用能源与道路车辆可持续发展战略研究（2005年数据））
2)将1)中能耗折算成标准煤
计算方法: (1)能耗直接乘以转换系数（Conversion factor），即

$$E_2 = E_1 * Conversionfactor$$

3)WTP阶段碳排放
计算方法：2)能耗乘以碳排放系数（carbon emission facators），即

$$EM = E_2 * Carbonemissionfactor$$

（附：carbon emission factors）

4. 车辆运营阶段

(1) 车辆燃油经济性

公交车：数据来源：北京市调查数据

BRT:数据来源：Energy consumption and emission of different transport modes in China, IFEU, NDRC

出租车：数据来源：北京市调查数据

私人汽车：数据来源：Long term energy and CO2 emission senario analysis in China urban transport, ERI, NDRC

混合动力汽车：数据来源：http://tyb.serc.gov.cn/found.jsp?TypeId=1313

摩托车：数据来源：Long term energy and CO2 emission senario analysis in China urban transport, ERI, NDRC

(2) 车辆碳排放

计算方法：(1) 中的燃油经济性乘以排放因子，即

$$EM = Fueleconomy * Carbonemissionfactor$$

（附：车辆的carbon emission factors）

5. 轨道交通运营能耗

(1) 车辆数

（数据来源：北京市交通调查）

(2) 能耗

分为牵引能耗和动力照明能耗

（数据来源：北京市交通调查）

(3) 客运量

（数据来源：北京市交通调查）

(4) 平均能耗

等于总能耗除以客运量，即

$$AvE = \frac{E}{Cap}$$

6. 其他数据

(1)中国电力发电量结构

水电、火电、核电发电总量

（数据来源：中国能源统计年鉴2007）

(2)各年的发电煤耗

（数据来源：中国能源统计年鉴2007）

(3)发电能耗

（数据来源：邹治平 马晓茜，水力发电工程的生命周期分析，水力发电，2004,4）

附：EXCEL文件

APPENDIX 7: SUMMARY OF ESTIMATION PROCESSES AND SOURCES OF PARAMETERS

Abbreviations:

elv.	*elevated*
udg.	*underground*
stn.	*station*
O/M	*operation & maintenance*
M/R	*maintenance & repair*

SHEET A

Cell	Value	Explanation	Source	Certainty
B14 (avg. power EF)	1.072 as national average	National average lifecycle emission factor of electricity based on 2007 data: 297.688 g CO_2e/MJ (1071.6768 g CO2e/kWh)	Ou et al, 2011	Produced by peer-reviewed research
	653 as South China Grid average	See Section 4.2 for detailed explanation	iCET, 2011; Lee et al 2004	Estimated using indirect data
K18:M20 (lifecycle CO_2e emissions of gasoline, diesel & CNG)	Several	Calculated using CNG energy content of 0.0382 MJ/L under standard temperature and pressure (STP)	Yan & Crookes, 2009 (Tables 1, 7 and Fig. 11)	Standard knowledge for gasoline and diesel; derived from peer-reviewed research for CNG

SHEET B

Cell	Value	Explanation	Source	Certainty
B5 (system power consumption rate per heavy rail-car-km)	5 kWh/vkt	See Section 4.2 for detailed explanation	Multiple, see Section 4.2	Definitely in the ballpark
B6 (system	4	Electricity consumption	Assumed.	Likely in the

power consumption rate per light rail-car-km)	kWh/vkt	of whole light rail system divided by total VKT (rail car-km traveled)		ballpark
B7 (std. diesel bus fuel economy)	0.4 L/vkt	Domestic estimate of average diesel consumption of standard bus	中华人民共和国交通部。2010。	Definitely in the ballpark
B8 (std. CNG bus fuel economy)	345 L/vkt	Domestic estimate of average natural gas (STP) consumption of standard bus	刘丽珍，侯凯。2009。	Definitely in the ballpark
B9 (std. diesel hybrid bus fuel economy)	0.31 L/vkt	Domestic estimate of diesel consumption of diesel-electric hybrid bus	中华人民共和国交通部。2010。	Likely in the ballpark
B10 (std. gasoline car fuel economy)	0.085 L/vkt	Domestic estimate of gasoline consumption of an 1.6 L domestically made sedan	申威，张阿玲，韩为建。2006。	Definitely in the ballpark
B11 (std. clean diesel car fuel economy)	0.068 L/vkt	U.S. EPA estimated diesel consumption of 2011 VW Jetta/Golf: 30(local)/41(highway) mpg (U.S.), or 7.84 (local)/5.74 (highway) L/100km	Volkswagen (U.S.) website	Definitely in the ballpark
B12 (std. gasoline hybrid car fuel economy)	0.05 L/vkt	Average of gasoline consumption of 2011 Toyota Prius (U.S. market: highway/local average of 50 mpg (U.S.) or 4.7 L/100km) and 2004 Toyota Prius produced by China FAW Group Corp. (average 5.2 L/100km)	Toyota (U.S.) website; 申威，等。2006。	Definitely in the ballpark
B13 (median-sized motorcycle fuel economy)	0.03 L/vkt	Gasoline consumption of domestic 100cc 4-stroke motorcycle	Cheery et al, 2009	Assumption used in peer reviewed research
B14 (median-sized e-bike power	2.1 kWh/100 vkt	Electricity consumption of domestic average electric bicycle	Cheery et al, 2009	Core assumption used in peer

consumption rate)				reviewed research

Cell	Value	Explanation	Source	Certainty
D19 (expressway O/M power consumption)	15200 kWh/ln-km-yr	Assuming 0.95W/m^2 (25 lx), 4000 h/yr lighting, and 4m wide lane (including shoulder)	城市道路照明设计标准, CJJ 45-2006	Likely in the ballpark
D20 (major arterial O/M power consumption)	15200 kWh/ln-km-yr	Ibid	Ibid	Ibid
D21 (minor arterial O/M power consumption)	10400 kWh/ln-km-yr	Assuming 0.65W/m^2 (12.5 lx), 4000 h/yr lighting, and 4m wide lane (including shoulder)	Ibid	Ibid
D22 (collector O/M power consumption)	8800 kWh/ln-km-yr	Assuming 0.55W/m^2 (9 lx), 4000 h/yr lighting, and 4m wide lane (including shoulder)	Ibid	Ibid
D23 (bike lane O/M power consumption)	8800 kWh/ln-km-yr	Ibid	Ibid	Ibid
D24 (rail ROW O/M power consumption)	0	Included in B5 and B6	n/a	n/a
D25(elv. expressway O/M power consumption)	15200 kWh/ln-km-yr	Assumed equal to D19	n/a	Likely in the ballpark
D26 (elv. rail ROW O/M power consumption)	0	Included in B5 and B6	n/a	n/a
D27 (udg. expressway O/M power consumption)	30400 kWh/ln-km-yr	Assuming 8000 h/yr lighting	城市道路照明设计标准, CJJ 45-2006	Likely in the ballpark
D28 (udg. rail ROW O/M power consumption)	0	Included in B5 and B6	n/a	n/a
D29 (BRT stn O/M power	2700 kWh/stn-	Assuming 180 m by 3 m platform, 1.25	城市道路照明设计标准, CJJ 45-2006	Likely in the

consumption)	yr	W/m² (30 lx), and 4000 h/yr lighting.		ballpark
D30 (light rail stn O/M power consumption)	0	Included in B5 and B6	n/a	n/a
D31 (heavry rail stn O/M power consumption)	0	Included in B5 and B6	n/a	n/a
D32 (elv. BRT stn O/M power consumption)	2700 kWh/stn-yr	Assuming same as at-grade BRT station		Likely in the ballpark
D33 (elv. light rail stn O/M power consumption)	0	Included in B5 and B6	n/a	n/a
D34 (elv. heavy rail stn O/M power consumption)	0	Included in B5 and B6	n/a	n/a
D35 (udg. Heavy rail stn O/M power consumption)	0	Included in B5 and B6	n/a	n/a
D36 (auto parking O/M power consumption)	456 kWh/spc-yr	Assuming 30 m^2/space, 3.8 W/m^2 (100 lx), and 4000 hr/yr lighting	公共停车场工程建设规范, 北京市地方标准 DB11/T 595—2008; 建筑照明设计标准, GB 50034-2004	Likely in the ballpark
D37 (bike parking O/M power consumption)	30.4 kWh/spc-yr	Assuming 2 m^2/space, 3.8 W/m^2 (100 lx), and 4000 hr/yr lighting	Ibid	Ibid
D38 (multilevel auto parking O/M power consumption)	570 kWh/spc-yr	Assuming 30 m^2/space, 3.8 W/m^2 (100 lx), and 5000 hr/yr lighting	Ibid	Ibid
D39 (multilevel bike parking O/M power consumption)	38 kWh/spc-yr	Assuming 2 m^2/space, 3.8 W/m^2 (100 lx), and 5000 hr/yr lighting	Ibid	Ibid
D40 (udg. auto parking O/M power consumption)	912 kWh/spc-yr	Assuming 30 m^2/space, 3.8 W/m^2 (100 lx), and 8000 hr/yr lighting	Ibid	Ibid
D41 (udg. bike parking O/M power consumption)	60.8 kWh/spc-yr	Assuming 2 m^2/space, 3.8 W/m^2 (100 lx), and 8000 hr/yr lighting	Ibid	Ibid

D42 (rail depot O/M power consumption)	0	Included in B5 and B6	n/a	n/a
D43 (bus depot O/M power consumption)	30.4 kWh/m^2-yr	Assuming 7.6 W/m2 (200 lx) and 4000 h/yr lighting	建筑照明设计标准, GB 50034-2004	Likely in the ballpark
D44 (BRT depot O/M power consumption)	30.4 kWh/m^2-yr	Assuming 7.6 W/m2 (200 lx) and 4000 h/yr lighting	Ibid	Ibid

SHEET C

Cell	Value	Explanation	Source	Certainty
G5 (lifecycle CO_2e emissions of a heavy rail car)	230000 kg	per heavy rail car (per BART car)	Chester, 2008 (Table 35); Chester and Harvath, 2009 (Table S3)	Transfer from foreign peer-reviewed estimates
G6 (lifecycle CO_2e emissions of a light rail car)	355000 kg	per light rail car (average of SF Muni and Boston Green Line trains)	ibid	Ibid
G7 (lifecycle CO_2e emissions of a std. diesel bus)	129000 kg	Per standard bus (U.S. 40ft bus)	Chester and Harvath, 2009 (Table S2)	Ibid
G8 (lifecycle CO_2e emissions of a std. CNG bus)	129000 kg		Assumed	Assumed based on G7
G9 (lifecycle CO_2e emissions of a hybrid bus)	129000 kg		Assumed	Ibid
G10 (lifecycle CO_2e emissions of std. gasoline car)	10000 kg	Per midsize sedan (2005 Camry)	Chester and Harvath, 2009 (Table S2)	Transfer from foreign peer-reviewed estimates
G11 (lifecycle CO_2e emissions of a std. clean diesel car)	10000 kg		Assumed	Assumed based on G10
G12 (lifecycle CO_2e emissions of a std. hybrid car)	10000 kg		Assumed	Ibid
G13 (lifecycle CO_2e emissions of a median-sized motorcycle)	1000 kg	Assuming proportional to weight (motorcycle 150 kg, vs. sedan 1500 kg)		Ibid
G14 (lifecycle CO_2e emissions of a	740 kg	Average of scooter style and bicycle style electric	Cherry et al, 2009	Results of peer-reviewed

median-sized e-bike)		bicycles		research
G15 (lifecycle CO_2e emissions of a bike)	100 kg		Cherry et al, 2009	Ibid

Cell	Value	Explanation	Source	Certainty
G19 (heavy rail vehicle M/R CO_2e emission)	0	Included in emissions of vehicle operation		n/a
G20 (light rail vehicle M/R CO_2e emission)	0	Included in emissions of vehicle operation		n/a
G21 (diesel bus M/R CO_2e emission)	0.03	U.S. 12 ft bus	Chester, 2008 (Table 13)	Transfer from foreign peer-reviewed research
G22 (CNG bus M/R CO_2e emission)	0.03		Assumed	Assumed based on G21
G23 (hybrid bus M/R CO_2e emission)	0.03		Assumed	Ibid
G24 (gasoline car M/R CO_2e emission)	0.015	U.S. sedan (2005 Camry)	Chester, 2008 (Table 10)	Transfer from foreign peer-reviewed research
G25 (diesel car M/R CO_2e emission)	0.015		Assumed	Assumed based on G24
G26 (hybrid car M&R CO_2e emission)	0.015		Assumed	Ibid
G27 (motorcycle M/R CO_2e emission)	0.005		Assumed	Ibid
G28 (e-bike M/R CO_2e emission)	0.002		Assumed	Ibid

G29 (bike M/R CO_2e emission)	0.001		Assumed	Ibid

Cell	Value	Explanation	Source	Certainty
G33 (lifecycle CO_2e of infrastructure capital - expressway)	553000 kg/ln-km	Calculated using results of U.S. interstate highway data and PaLATE	Chester, 2008 (Appendix B)	Transfer from foreign peer-reviewed research
G34 (lifecycle CO_2e of infrastructure capital – major arterial)	423000 kg /ln-km	Calculated using results of U.S. major urban arterial data and PaLATE	Ibid	Ibid
G35 (lifecycle CO_2e of infrastructure capital – minor arterial)	423000 kg /ln-km	Calculated using results of U.S. minor urban arterial data and PaLATE	Ibid	Ibid
G36 (lifecycle CO_2e of infrastructure capital - collector)	337000 kg /ln-km	Calculated using results of U.S. urban collector road data and PaLATE	Ibid	Ibid
G37 (lifecycle CO_2e of infrastructure capital – bike lane)	259000 kg /ln-km	Calculated using results of U.S. urban local road data and PaLATE	Ibid	Ibid
G38 (lifecycle CO_2e of infrastructure capital – rail ROW)	1106000 kg /ln-km	Calculated assuming total GHG emissions equal 2 expressway lanes, based on estimated cost ratio in Wang (2008, 2010)	Wang, 2008 (Tables A3.1 and A3.3)	Using G33 and peer-reviewed research result on cost relationships between different infrastructure capitals
G39 (lifecycle CO_2e of infrastructure capital – elv. expressway)	1659000 kg /ln-km	Calculated assuming total GHG emissions equal 3 times of at-grade facilities, based on	Wang, 2008 (Tables A3.1)	Ibid

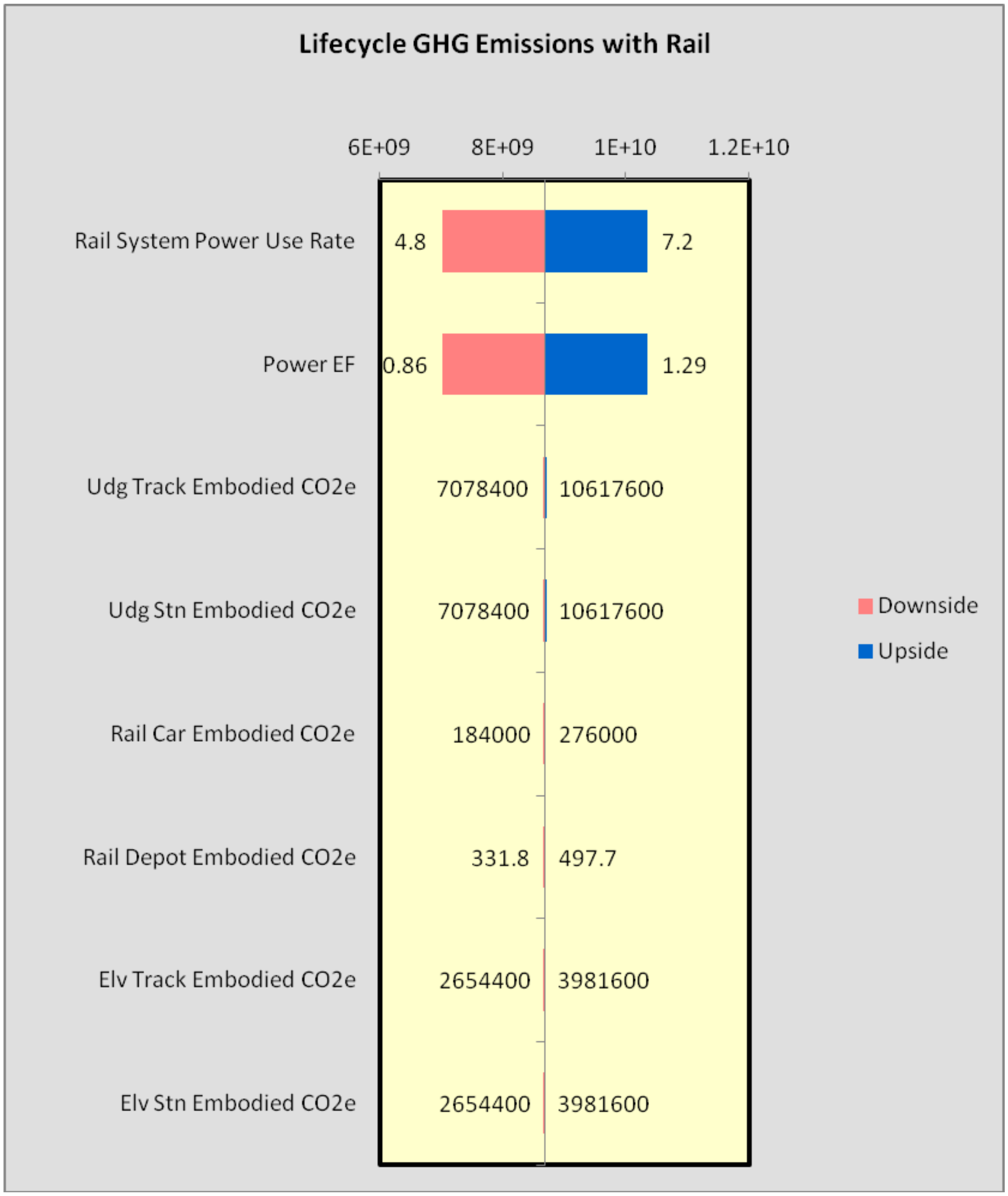
		estimated cost ratio in Wang (2008, 2010)		
G40 (lifecycle CO_2e of infrastructure capital – elv. rail ROW)	3318000 kg /ln-km	Ibid	Ibid	Ibid
G41(lifecycle CO_2e of infrastructure capital – udg. expressway)	4424000 kg /ln-km	Calculated assuming total GHG emissions equal 8 times of at-grade facilities, based on estimated cost ratio in Wang (2008, 2010)	Ibid	Ibid
G42(lifecycle CO_2e of infrastructure capital – udg. rail ROW)	8848000 kg /ln-km	Ibid	Ibid	Ibid
G43(lifecycle CO_2e of infrastructure capital – BRT stn.)	74655 kg /stn	Calculated assuming 3 m by 180 m platform and same unit space emissions as expressway		Based on G33 and prevailing BRT stn. size in China
G44(lifecycle CO_2e of infrastructure capital – light rail stn.)	74655 kg /stn	Assuming same as BRT station		Based on G43
G45(lifecycle CO_2e of infrastructure capital – heavy rail stn.)	1106000 kg /stn	Calculated assuming 7500 m^2 construction area according to Wang (2008, 2010) and same unit space emissions as expressway	Wang, 2008 (Section A3.1.1.2)	Based on G33 and peer-reviewed research result of stn. size
G46 (lifecycle CO_2e of infrastructure capital – elv.	223965 kg /stn	Calculated assuming total GHG emissions equal 3 times of	Wang, 2008 (Tables A3.1)	Based on G43 and peer-reviewed research result on cost relationships

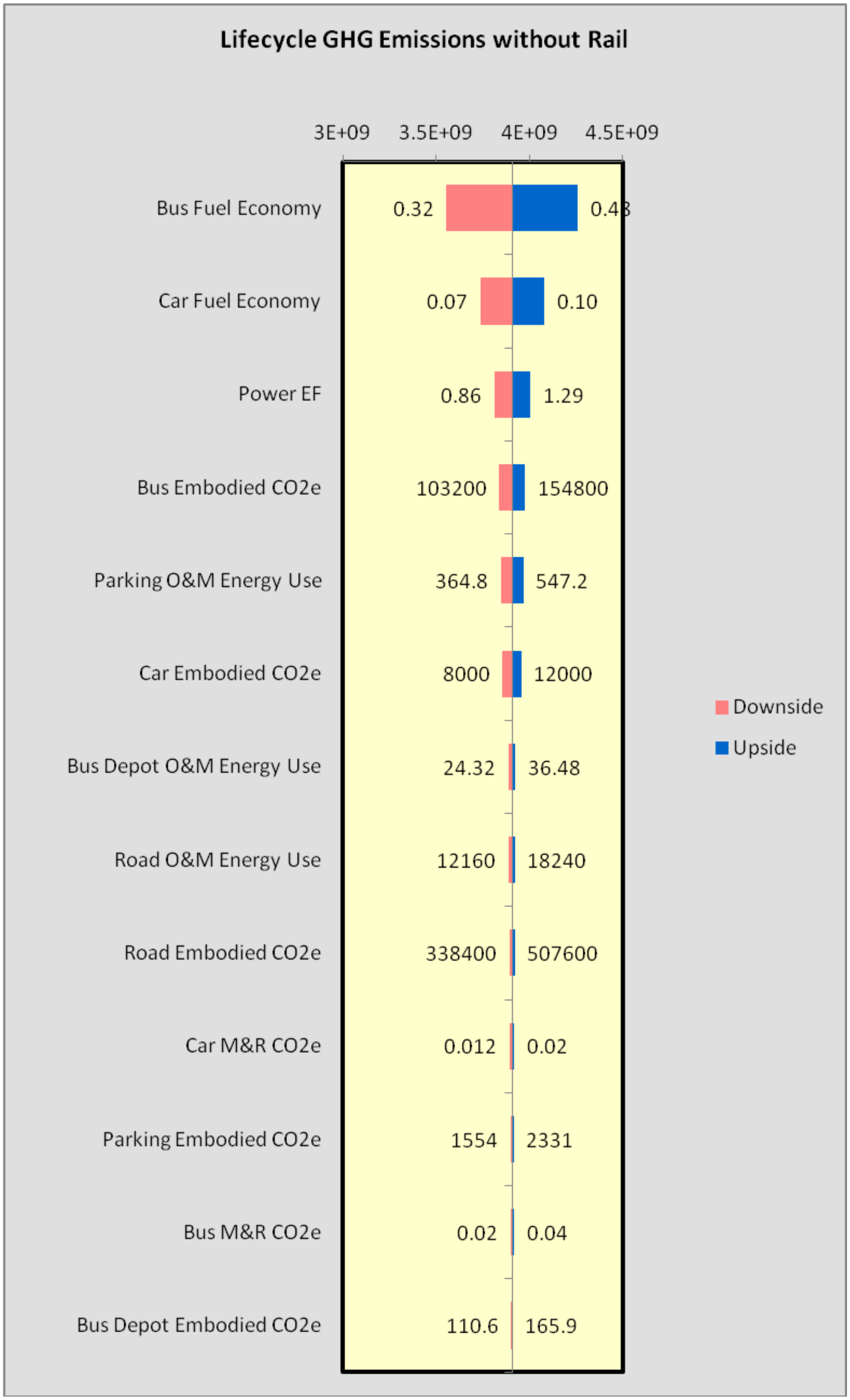
BRT stn.)		at-grade facilities, based on estimated cost ratio in Wang (2008, 2010)		
G47 (lifecycle CO_2e of infrastructure capital – elv. light rail stn.)	223965 kg /stn	Ibid	Ibid	Based on G44 and peer-reviewed research result on cost relationships
G48 (lifecycle CO_2e of infrastructure capital – elv. heavy rail stn.)	3318000 kg /stn	Ibid	Ibid	Based on G45 and peer-reviewed research result on cost relationships
G49 (lifecycle CO_2e of infrastructure capital – udg. heavy rail stn.)	8848000 kg /stn	Calculated assuming total GHG emissions equal 8 times of at-grade facilities, based on estimated cost ratio in Wang (2008, 2010)	Ibid	Ibid
G50 (lifecycle CO_2e of infrastructure capital – auto parking)	1942.5 kg /spc	Calculated assuming unit space emission equals77% of local road and 30 m^2/space	Wang, 2008 (Table A3.4); 公共停车场工程建设规范, 北京市地方标准 DB11/T 595—2008	Estimated based on peer-reviewed research result
G51 (lifecycle CO_2e of infrastructure capital – bike parking)	129.5 kg /spc	Calculated assuming unit space emission equals77% of local road and 2 m^2/space	Ibid	Ibid
G52 (lifecycle CO_2e of infrastructure capital – multilevel auto parking)	5827.5 kg /spc	Calculated assuming total GHG emissions equal 3 times of at-grade facilities, based on estimated cost ratio in Wang (2008, 2010)	Wang, 2008 (Tables A3.1)	Based on G50 and peer-reviewed research result on cost relationships

G53 (lifecycle CO_2e of infrastructure capital – multilevel bike parking)	388.5 kg /spc	Ibid	Ibid	Ibid
G54 (lifecycle CO_2e of infrastructure capital – udg. auto parking)	15540 kg /spc	Calculated assuming total GHG emissions equal 8 times of at-grade facilities, based on estimated cost ratio in Wang (2008, 2010)	Ibid	Ibid
G55 (lifecycle CO_2e of infrastructure capital – udg. bike parking)	1036 kg /spc	Ibid	Ibid	Ibid
G56 (lifecycle CO_2e of infrastructure capital – rail depot)	414.75 kg /m^2	Assuming unit space emission equals that of elevated expressway		Assumed based on G39
G57 (lifecycle CO_2e of infrastructure capital – bus depot)	138.25 kg /m^2	Assuming unit space emissions equals that of at-grade expressway		Assumed based on G33
G58 (lifecycle CO_2e of infrastructure capital – BRT depot)	138.25 kg /m^2	Assuming unit space emissions equals that of at-grade expressway		Ibid

Cells G62 through G87 are obtained by multiplying B14 of Sheet A with values of D19 through D44 of Sheet B.

APPENDIX 8: SENSITIVITY ANALYSIS CHARTS (SINGLE PARAMETER ±20% VARIATION)





Lifecycle GHG Emissions without Rail
3E+09
3.5E+09
4E+09
4.5E+09
Bus Fuel Economy
0.32
0.48
Car Fuel Economy
0.07
0.10
Power EF
0.86
1.29
Bus Embodied CO2e
103200
154800
Parking O&M Energy Use
364.8
547.2
Car Embodied CO2e
8000
12000
Bus Depot O&M Energy Use
24.32
36.48
Road O&M Energy Use
12160
18240
Road Embodied CO2e
338400
507600
Car M&R CO2e
0.012
0.02
Parking Embodied CO2e
1554
2331
Bus M&R CO2e
0.02
0.04
Bus Depot Embodied CO2e
110.6
165.9
Downside
Upside

Transport Research Support

Transport Division

Transport, Water and
Information and Communication
Technology Department

The World Bank

1818 H Street NW

Washington DC 20433

USA

www.worldbank.org/Transport

DFID Department for International Development