STEEL VERSUS STEEL-REINFORCED CONCRETE BRIDGES: ENVIRONMENTAL ASSESSMENT

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ABSTRACT: Bridge material selection has traditionally been based on engineering and economic criteria. With the increasing interest of the public, industry, and government in sustainable development, environmental assessment in construction is becoming more important. However, we need metrics and data on design alternatives for effective decision making. In this paper, we present results of a life cycle inventory analysis of steel and steel-reinforced concrete bridge girders, based on publicly available data. We find that for the initial construction of equivalent designs for a particular location, a steel-reinforced concrete bridge generally has lower environmental effects than a steel bridge. The expected design life of the two types of bridges is influenced by wear and tear, but also by obsolescence. The uncertainty in bridge design life and related data uncertainties make comparisons based on annualized environmental effects difficult. The steel bridges' beneficial reuse and recycling rates may result in lower annualized environmental effects. In particular applications, however, one material might be preferred over the other due to engineering, aesthetic, or economic criteria, regardless of overall environmental effects.

INTRODUCTION

Bridge superstructure designs typically involve steel or steel-reinforced concrete, or a combination of the two materials. The two designs are competitive, with numerous examples of both types in use. The traditional criteria for selecting a particular design have been engineering requirements, initial and life cycle costs, experience with and availability of a particular material or technology, aesthetics, and the ability to erect the structure under local environmental conditions (climate, topography, etc.). With a steel and steel-reinforced concrete comparison, we would like to draw attention to the environmental implications of particular bridge material choices and designs. The environmental assessment of the two materials is best performed using life cycle assessment (LCA).

LIFE CYCLE ASSESSMENT (LCA)

LCA is a method that systematically assesses and analyzes the environmental effects of the five various stages of a product's or process' entire life cycle: (1) the materials extraction phase; (2) the materials processing stage; (3) the manufacturing stage; (4) the use phase; and (5) the ultimate disposal stage (end-of-life). LCA has three parts: (1) the inventory analysis quantifies the environmental effects; (2) the impact analysis estimates the effects of these burdens on humans and nature; and (3) the improvement analysis identifies areas and means of possible improvement. There are many efforts in the world to produce LCAs for a variety of products and processes (Vigon et al. 1993; Graedel and Allenby 1995). Data are gathered either directly from participants in the life cycle chain of a product or process, or used from libraries of past LCAs. For these reasons, LCA studies, in general, have been expensive and time-consuming. If a product is redesigned, the analysis has to be redone. Most LCA studies performed to date have been, in fact, inventory analyses, with some attempt to include improvement analysis. Impact analysis has especially been difficult to perform due to a lack of appropriate scientific data. Interpretation of the results has been controversial, depending on the objectives of the reader, and on the weight assigned to each of the environmental effects quantified (Portney 1994). Many LCA studies produced to date have not been published due to the proprietary data use or the controversial results. Despite its limitations, there is an articulated need for LCA studies, as well as better metrics and data, in decision making for sustainable development.

In this paper an economic input-output-based life cycle assessment (EIO-LCA) is used. This method is predicated on the fact that in a modern economy every sector contributes, directly or indirectly, to every other sector (Lave et al. 1995; Hendrickson et al. 1998). The EIO-LCA model employs economic input-output analysis, invented by Wassily Leontief in the 1930s (for which he received a Nobel prize) (Leontief 1986), and commodity-by-commodity input-output matrices, compiled by the Department of Commerce ("Input-output" 1994) in the United States, and available in similar form for most developed and industrializing countries. Economic input-output analysis explicitly accounts for all of the direct and indirect inputs to producing a product or service by using the input-output matrices of a national economy. For example, cement production and electricity are direct inputs of concrete production, but many agricultural and service sectors are indirect, or second, third, etc., tier suppliers (by being suppliers, or suppliers of suppliers of direct suppliers). In addition, electricity is required to produce electricity, and cement is needed for cement manufacturing. Suppose that the production of \$1 of concrete requires \$0.20 of inputs from the cement industry, which in turn requires \$0.10 of coal mining, etc. The conventional approach would have to limit the number of process flows and suppliers to complete the assessment. The input-output model accounts for all the direct and indirect economic effects.

Environmental input-output analysis complements the economic input-output analysis by linking economic data with resource use (such as energy, ore, and fertilizer consumption) and environmental output [such as toxic chemical discharges, Subtitle C hazardous waste generation and management as defined in the Resource Conservation and Recovery Act (U.S. EPA 1993), ozone depletion potential, and conventional air pollutant emissions] data. In the above example, total direct and indirect (upstream) emissions of species i per \$1 of concrete product can be calculated by taking the sum: (concrete production's direct emissions of i per \$1 of concrete) + 0.20*(cement industry's direct emissions of i per \$1 of cement) + 0.20*0.10*(coal mining's emissions of i per \$1 of

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coal) + other terms representing the inputs to coal mining, etc. In reality, there are many more inputs in each industry than described here. We have used a 519*519 commodity-by-commodity matrix of the U.S. economy that identifies and quantifies what those inputs are for U.S. industries and commodities.

In this article, we present a life cycle inventory analysis of steel and steel-reinforced concrete bridge girders. We used the EIO-LCA method to assess the environmental effects of the materials extraction, the materials processing, and the manufacturing stages, and data from literature for the other life cycle phases. This article is based on an unpublished doctoral dissertation (Horvath 1997).

DESIGN AND MATERIAL COMPOSITION OF BRIDGE GIRDERS

Alternative designs for the bridge on U.S. 231 over the White River in Indiana (Spaans 1997) were selected. Bids were solicited for a 428.2 m (1,405 ft) long and 14.7 m (48.3 ft) wide bridge with either steel or reinforced concrete girders. We used the data for the low bids using steel plate girders and posttensioned concrete girders. Table 1 presents the cost figures for the two designs. A concrete deck was designed for both the steel and the concrete girder bridge, and the cost of the deck and the cross girders (with the rebar in deck and cross girders) in both cases were comparable. It is evident from Table 1 that the cost of the substructure for the two designs was close, with the concrete bridge 13% less expensive. There was a difference in the cost of the expansion joints ($53,000 for the steel design and $35,000 for the concrete design) and in the cost of bearings ($94,000 for the steel design versus $20,000 for the concrete design). Only the girders were compared since the difference between the two designs is mostly due to the difference in the cost of girder materials.

The steel plate girder bridge design had eight spans of various lengths, from 27.4 to 54.9 m (90 to 180 ft), and two additional spans totaling 61.7 m (202.5 ft) made with AASHTO Type IV girders. The posttensioned bulb-tee girder design had nine equal spans of 40.8 m (133.75 ft) and two additional spans made with the same type and length of girders as the steel alternative. Since the two additional spans were identical, we neglected them in our analysis. Overall, the concrete alternative had a $1,000,000 lower initial cost (a 37% savings).

PERFORMING EIO-LCA

The EIO-LCA method was used to assess the environmental effects of the materials extraction, the materials processing, and the manufacturing stages, as if $781,000 worth of steel-reinforced concrete girders, and $1,756,000 worth of steel girders were purchased (final demand). The two girder materials were represented by sectors in the economic input-output matrix. For the concrete girder, we used the sector concrete products (except block and brick) (Standard Industrial Classification, SIC, code 3272). For the steel girder, the fabricated structural metal sector (SIC 3441) was used. Producing the concrete girders generated an intermediate demand (in input products and services) of $686,000 in the economy (for a total demand of $781,000 + $686,000 = $1,467,000), and producing the steel girders had an intermediate demand of $2,142,000 (for a total demand of $3,898,000).

TABLE 1. Low Bids for U.S. 231 over the White River in Indiana (Spaans 1997)

Design (1)	Cost (2)
Steel alternative	
Steel girders + bearings	1,756,000 + 93,870
Expansion joints	52,795
Concrete deck and cross girders + rebar	565,628 + 315,748
Substructure	855,039
Bridge, total	3,639,080
Cost per square foot of steel bridge	53.59
Concrete alternative	
Concrete girders + bearings	781,000 + 20,000
Post-tensioning + erection	135,000 + 75,000
Expansion joints	34,720
Concrete deck and cross girders + rebar	575,009 + 281,831
Substructure	747,191
Bridge, total	2,649,751
Cost per square foot of concrete bridge	39.02

Several resource input requirements and environmental burdens have been quantified. Resource inputs include consumption of electricity, fuels, ores, and fertilizers ("Input-output" 1994). Fertilizers are not direct inputs to either steel or concrete manufacturing, but they are part of the long chain of indirect suppliers, that is, upstream suppliers of direct suppliers such as forestry products. Environmental outputs include toxic chemical discharges to air, water, land, underground injection wells, and transfers to off-site treatment plants (U.S. EPA 1995), ozone depletion potential of chemical releases (U.S. EPA 1995); Ozone 1997—website: http://www.epa.gov/ozone/title6/procu/procu.html), hazardous waste generation and management (U.S. EPA 1993), and conventional air pollutant emissions ("Input-output" 1994; "Air CHIEF" 1995). Similar to the resource input requirements, the environmental effects of not only the direct suppliers (such as the cement industry for concrete), but the indirect suppliers as well (such as the agricultural sector for concrete) are included in this assessment.

UNCERTAINTY IN DATA

All of the data used in this study are uncertain. For example, concrete bridge girders were estimated by a sector (concrete products) that include not only girders but other products, with perhaps different environmental implications. Furthermore, the toxic chemical releases' data are obtained from the EPA's Toxics Release Inventory (TRI), collected from manufacturing plants in the United States. Facilities have to report to the TRI; they do not have to measure their emissions but do have to estimate. This inevitably leads to inaccuracies (U.S. GAO 1991). Similar uncertainties exist regarding RCRA Subtitle C hazardous waste data. Conventional pollutant emissions are based on the fuel consumption of facilities, and the AP-42 emissions factors ("Air CHIEF" 1995) from the EPA. The AP-42s are estimates of air emissions from processes. Resource input calculations are based on data gathered by the U.S. Department of Commerce. Companies' own accounts of these costs are not perfect, and many facilities fail to report them completely. Therefore, the results obtained in this LCA must be analyzed in light of the uncertainty in the data.

RESOURCE INPUT REQUIREMENTS

Table 2 contains a summary of the resource input requirements associated with materials extraction, materials processing, and manufacturing steel and steel-reinforced concrete girders for the highway bridge in our example. With the exception of some fertilizer consumption, all other resource inputs appear to be higher for the steel alternative. If we convert fuel usage by type into a common unit, it is roughly 12,000 GJ of energy for the concrete and 33,000 GJ of energy for the steel design.

ENVIRONMENTAL OUTPUTS

Table 3 contains a summary of the outputs associated with the materials extraction, materials processing, and manufac-

TABLE 2. Environmental Effects of Steel-Reinforced Concrete (Concrete + Reinforcing) and Steel Production for Example Equivalent Bridge Girder Design—Summary of Resource Inputs

Resource inputs (1)	Concrete (2)	Steel (3)	Ratio (concrete/steel) (4)
Electricity (kW·h million)	0.4	1.4	0.3
Coal and coke			
Anthracite coal (t)	0.5	1.4	0.4
Bituminous coal (t)	300	800	0.4
Coke (t)	8	100	0.1
[Total] (t)	309	901	0.3
Fuels			
Natural gas (t)	20	60	0.3
Liquefied natural gas (t)	3	5	0.6
Motor gasoline (t)	10	20	0.5
Aviation fuel (t)	0.1	0.2	0.5
Jet fuel (t)	2	7	0.3
Kerosene (t)	0.004	0.005	0.8
Light fuel oil (t)	30	50	0.6
Heavy fuel oil (t)	7	20	0.4
Liquefied petroleum gas (t)	6	10	0.6
[Total] (t)	78	172	0.5
Ores			
Iron ore (t)	70	900	0.08
Ferrous ore (dollars)	100	700	0.1
Copper ore (t)	20	250	0.08
Bauxite (t)	2	8	0.3
Gold ore (t)	30	250	0.1
Silver ore (t)	5	50	0.1
Lead-zinc ore (dollars)	4	300	0.01
Uranium-vanadium ore (dollars)	20	300	0.07
Fertilizers			
Ammonia (t)	1	2	0.5
Ammonium nitrate (t)	1	0.5	2
Ammonium sulfate (t)	0.02	0.04	0.5
Urea (t)	0.1	0.1	1
Organic fertilizers (t)	0.01	0.01	1
Superphosphate (t)	0.3	0.4	0.8
Phosphatic fertilizers (t)	0.001	0.001	1
[Total] (t)	2.4	3.0	0.8

TABLE 3. Environmental Effects of Steel-Reinforced Concrete (Concrete + Reinforcing) and Steel Production for Example Equivalent Bridge Girder Design—Summary of Environmental Outputs

Environmental outputs (1)	Concrete (2)	Steel (3)	Ratio (concrete/steel) (4)
TRI air releases (t)	0.1	0.7	0.1
TRI water releases (t)	0.02	0.07	0.3
TRI land releases (t)	0.06	0.6	0.1
TRI underground releases (t)	0.04	0.2	0.2
TRI total releases to environment (t)	0.2	1	0.2
TRI total releases and transfers (t)	0.8	7	0.1
CMU-ET for air releases (t H_2SO_4 equivalent)	0.03	0.3	0.1
CMU-ET for water releases (t H_2SO_4 equivalent)	0.01	0.05	0.2
CMU-ET for land releases (t H_2SO_4 equivalent)	0.3	3	0.1
CMU-ET for underground releases (t H_2SO_4 equivalent)	0.02	0.1	0.2
CMU-ET for total releases (t H_2SO_4 equivalent)	0.4	3	0.1
CMU-ET for releases and transfers (t H_2SO_4 equivalent)	2	20	0.1
Ozone depletion potential (t CFC-11 equivalent)	0.002	0.008	0.3
RCRA hazardous waste generated (t)	20	70	0.3
RCRA hazardous waste managed (t)	20	40	0.5
RCRA hazardous waste shipped (t)	3	30	0.1
SO_2 (t)	10	30	0.3
NO_x (t)	4	10	0.4
Methane (t)	0.03	0.05	0.6
Volatile organic compounds (t)	0.4	0.8	0.5

Note: Numbers may not sum due to rounding.

turing stages of steel and concrete bridge girders. Three major groups of environmental impacts are quantified in this assessment: (1) TRI chemical emissions; (2) hazardous waste generation; and (3) conventional air pollutant emissions. For the TRI discharges, we assessed both the amounts of TRI emissions as reported by facilities to the EPA, without regard to the relative toxicity of the emissions, and the amounts of TRI emissions weighted by relative toxicity. The latter method was developed to account for the fact that a kilogram of a TRI discharge may be more or less environmentally damaging than another kilogram of a different chemical release (Horvath et al. 1995). For example, a kilogram of lead emitted to the air is more toxic than an equal amount of methanol. The weighting of TRI chemicals is performed using the threshold limit values (TLVs), which represent a maximum concentration level in air to which workers may be exposed over a typical work week without adverse health effects. Although not all TLVs are good measures of toxicity and do not account for the different fate and transport of substances in the environment, they are available for the greatest number of TRI chemicals and are a reasonable first approximation of human toxicity. We call the weighting method Carnegie Mellon University-Equivalent Toxicity (CMU-ET), and the weighted pounds of emissions are normalized to kilograms of sulfuric acid equivalent.

After examining the environmental outputs of concrete and steel girder manufacturing, we find that emissions appear to be higher for the steel girders.

USE PHASE ENVIRONMENTAL EFFECTS

Maintenance operations during the lifetime of a bridge have environmental consequences. Unfortunately, maintenance costs are difficult to obtain. In this assessment only the painting of the steel structure, as perhaps the most important maintenance need for a steel bridge, has been considered (Rainer 1990). We estimated that ~6,040 m^2 (65,000 ft^2) of steel girder surface needs to be coated for the steel design alternative in the current example, and that only one coating is required. (Note that the initial painting of the girders and the painting of railings was not assessed above.) A catalog ("Means" 1987) lists a unit material price of $0.10 per ft^2 or $1.08 per m^2 for bridge repainting. It was assumed that bridge paint is produced by the paints and allied products sector (SIC 285), and that we need to purchase $6,500 worth of paint for a single job. A maintenance operation such as bridge repainting is repeated several times during the lifetime of a bridge. It is estimated (Rainer 1990) that a typical preventive maintenance plan for a large steel bridge requires a repaint every eight years. This is applicable to our steel girder bridge example. If we assume that the steel bridge will last up to 80 years, then it will be repainted 10 times, including the first painting.

It is difficult to assess the relative magnitude of inputs and outputs for the paint without comparing them to another example. Here we compare the paint figures to the inputs and outputs of steel bridge girders. Table 4 compares the resource inputs. Table 5 compares the environmental outputs of the manufacture of the steel girders and the paint for ten repaint jobs for the steel bridge. Note that, as expected, with the exception of conventional air pollutants, all resource requirements and environmental outputs are at least several times higher for the girder production. Of course, if the bridge would be repainted more often and in more layers, the differences in the numbers would be smaller. However, Table 5 shows a sur-

TABLE 4. Environmental Effects of Paint (for Ten Repaint Jobs) and Steel Manufacturing for Typical Highway Bridge—Summary of Resource Inputs

Resource inputs (1)	Paint (2)	Steel (3)	Ratio (paint/steel) (4)
Electricity (kW · h million)	0.04	1.4	0.03
Coal and coke			
Anthracite coal (t)	0.02	1.4	0.01
Bituminous coal (t)	8	800	0.01
Coke (t)	0.4	100	0.004
[Total] (t)	8	901	0.009
Fuels			
Natural gas (t)	3	60	0.05
Liquefied natural gas (t)	0.3	5	0.06
Motor gasoline (t)	0.3	20	0.02
Aviation fuel (t)	0.004	0.2	0.02
Jet fuel (t)	0.2	7	0.03
Kerosene (t)	0.0002	0.005	0.04
Light fuel oil (t)	2	50	0.04
Heavy fuel oil (t)	0.5	20	0.03
Liquefied petroleum gas (t)	0.3	10	0.03
[Total] (t)	7	172	0.04
Ores			
Iron ore (t)	2	900	0.002
Ferrous ore (dollars)	20	700	0.03
Copper ore (t)	3	250	0.01
Bauxite (t)	3	8	0.4
Gold ore (t)	2	250	0.008
Silver ore (t)	0.4	50	0.008
Lead-zinc ore (dollars)	20	300	0.07
Uranium-vanadium ore (dollars)	2	300	0.007
Fertilizers			
Ammonia (t)	0.4	2	0.2
Ammonium nitrate (t)	0.02	0.5	0.04
Ammonium sulfate (t)	0.006	0.06	0.2
Urea (t)	0.02	0.1	0.2
Organic fertilizers (t)	0.002	0.01	0.2
Superphosphate (t)	0.06	0.40	0.2
Phosphate fertilizers (t)	0.0001	0.001	0.1
[Total] (t)	0.5	3	0.2

prising result. Sulfur dioxide, oxides of nitrogen, methane, and volatile organic compound emissions are significantly higher for the paint manufacturing than for the production of all girders for the example highway bridge. Therefore, the environmental effects of the use phase of products can be very important in life cycle assessment.

END-OF-LIFE OPTIONS FOR BRIDGE GIRDERS

Steel Girders

Steel bridge girders last a long time. Some steel bridges constructed in the last century still survive with regular maintenance and repair. The decommissioning of steel bridges is often the practice not because the girders reach the end of their structural life, but because of functional obsolescence. Changing traffic volumes, loads, or patterns may require a wider, stronger, larger, longer bridge (Lemer 1996). Often the major traffic routes move away from the bridge. Especially in remote areas, or where historic preservation efforts have saved them, many steel bridges have not been deconstructed, but left in place, closed for traffic. In some instances, with smaller bridges, the superstructure has been reused at another location where the old bridge structure was sufficient for the local traffic. This represents a beneficial reuse of steel girders. Since they can be a feedstock for new steel production, it is presumed that, if not left in place or reused, obsolete steel bridge girders are recycled. Comprehensive, national data on steel bridge girder recycling in the United States are unavailable.

TABLE 5. Environmental Effects of Paint (for Ten Repaint Jobs) and Steel Manufacturing for Typical Highway Bridge—Summary of Environmental Outputs

Environmental outputs (1)	Paint (2)	Steel (3)	Ratio (paint/steel) (4)
TRI air releases (t)	0.06	0.7	0.09
TRI water releases (t)	0.008	0.07	0.1
TRI land releases (t)	0.008	0.6	0.01
TRI underground releases (t)	0.05	0.2	0.3
TRI total releases to environment (t)	0.2	1	0.2
TRI total releases and transfers (t)	0.4	7	0.06
CMU-ET for air releases (t H_2SO_4 equivalent)	0.008	0.3	0.03
CMU-ET for water releases (t H_2SO_4 equivalent)	0.003	0.05	0.06
CMU-ET for land releases (t H_2SO_4 equivalent)	0.06	3	0.02
CMU-ET for underground releases (t H_2SO_4 equivalent)	0.03	0.1	0.3
CMU-ET for total releases (t H_2SO_4 equivalent)	0.08	3	0.03
CMU-ET for releases and transfers (t H_2SO_4 equivalent)	0.2	20	0.01
Ozone depletion potential (CFC-11 equivalent)	0.002	0.008	0.3
RCRA hazardous waste generated (t)	8	70	0.1
RCRA hazardous waste managed (t)	3	40	0.08
RCRA hazardous waste shipped (t)	0.8	30	0.03
SO_2 (t)	200	30	67
NO_x (t)	80	10	8
Methane (t)	0.8	0.05	16
Volatile organic compounds (t)	20	0.8	25

The U.S. statistics on steel product shipments (AMM 1996) are broken down by construction uses, such as structural shapes. However, steel bridge girders are uniquely designed and manufactured products, welded and bolted together from steel plates. Steel plates, on the other hand, are used not only in construction, but in automotive applications, in oil and gas industry, in mechanical equipment manufacturing, in shipbuilding, etc. Therefore, it is difficult to determine how much steel plate is used in bridge applications on a yearly basis.

Due to the lack of comprehensive data on national steel statistics, data from a joint Federal Highway Administration (FHWA)—EPA study (Bloomquist et al. 1993) were used to estimate the recycling rates for steel girders. This report contains results from a survey of the recycling practices of 29 state highway agencies in the United States conducted at the end of 1992. Data were collected on bridge superstructures, i.e., on beams and decks, not solely on steel structural members. Therefore, the results could be skewed if bridge decking reuse or recycling rates had been different from those for the girders. The results of the survey indicate that reuse of obsolete bridge steel superstructures has been practiced by 20 out of 29 states. Rates of reuse range from 1% in Maryland and Wyoming to 100% in Vermont, with 13 states between 1 and 20%, and six states above 40%. However, there is an overlap between reuse and recycling in this report. Recycling of steel superstructures in this context meant cutting, breaking, or modifying the steel superstructure for use in a different highway application, or reusing or storing it for subsequent use after straightening, painting, or minor repair. Nine states reported recycling rates between 5%, in Arizona, and 100%, in Utah, with seven states achieving more than a 50% recycling rate. Disposal options included sales as scrap, landfilling, giving the superstructure to a contractor or to others, and disposing of unusable or unsuitable items. Therefore, even though the disposal rates were the highest of all three end-of-initial-life options for 21 states out of the 29, it did not automatically mean landfilling. Eleven states explicitly noted that the obsolete steel became the property of the contractor who dismantled it, who in turn could have reused, recycled, or eventually landfilled it. One state, Connecticut noted that only unusable items were landfilled. Three states sold the obsolete steel as scrap. Therefore, the reuse and recycle rates in Bloomquist et al. (1993) (17 and 21%, respectively) are actually minimum rates. For example, Virginia reported that 100% of the dismantled steel superstructure was disposed of, but noted that it was sold as scrap and therefore recycled. For the same state, the recycling rate was reported as zero, when in effect it was 100%. Data for five Canadian provinces are also provided in the report, exhibiting a similar trend to the U.S. states.

Of course, these survey results should be interpreted carefully. There might have been significant reporting errors, and it was unspecified in the survey what period the report had covered (e.g., 1992 only, last three years, or standard practice). Given that only a small number of bridges are decommissioned and deconstructed every year in individual states, the survey might not be representative of actual time trends.

Concrete Girders

Similarly to the steel design alternative, the best source of statistics on concrete girder recycling is the joint FHWA-EPA study of 1993 (Bloomquist et al. 1993). However, the end-of-life options for concrete beams seem to be much more limited than for steel beams. Of the 27 states responding to the survey in this study, only six reported any reuse of old concrete girders, with the rates ranging from 10 to 50%. Recycling has only been reported by four states at a 10, 50, 70, and 100% rate, respectively. Consequently, a large majority of the states reported a 100% disposal rate, with the option of the old concrete beams going into landfills or being given to contractors. The contractors may have reused or recycled the old concrete beams, thus, raising their reuse and recycling rates, or they may have eventually landfilled them, for lack of a better use. Therefore, as with the steel alternative, the reported reuse and recycling rates may be underestimated. Upon examining the numbers for five Canadian provinces, it is noted that no reuse and, in only one province, was recycling observed. Of course, data and survey quality issues might make these numbers unreliable or unrepresentative, as with the steel girder option. Unrepresentativeness is possible, given the large differences in the reported practices: (1) two states observed a 50% reuse rate, and (2) one state reported a 100% recycling rate when many other states might have landfilled their old concrete beams entirely.

DISCUSSION

Some environmental effects associated with the materials extraction, materials processing, and manufacturing stages of steel-reinforced concrete and steel bridge girders for equivalent designs are presented previously. The concrete design appears to have lower environmental effects overall. Of course, the results might be different for another design as every bridge is unique in its design and material content.

The bridge girders were compared based on a summary of environmental effects. However, there might be a difference in the expected design life of the two materials. For a more realistic comparison, we need to take into account longevity and annualize environmental effects. However, comprehensive statistics on the expected life of steel and concrete bridges are hard to find. One source (Veshosky and Nickerson 1993) estimates the life of bridges in Belgium, Japan, Sweden, and Switzerland at 47–76 years for steel, and 47–86 years for reinforced concrete (prestressed concrete bridges last 21–86 years), therefore, they are comparable. Steel bridges have been constructed for a longer period of time than concrete bridges. As a result of regular maintenance, extensive repair and modifications, some parts of steel bridges can survive for 100 years or more. The first prestressed concrete bridge was not finished until 1951 (Marland and Weinberg 1988), and it was the building of the Interstate highway system that brought about the prevalence of concrete highway bridges in the U.S. Of course, six factors other than time may also influence the useful life of bridges: (1) flood; (2) fire; (3) wind; (4) foundation scour; (5) war; and (6) collision (Marland and Weinberg 1988). Most importantly, with everincreasing traffic and changing societal demands, functional obsolescence, not time, might render any type of bridge obsolete long before it fails structurally (Lemer 1996).

How many resources are embedded in the steel bridges, and what percentage of the national emissions does the manufacturing of steel bridge girders account for? Of the currently 580,000 bridges in the United States, we do not know exactly how many have steel versus concrete superstructures. We may assume that half of the bridges (290,000) were steel, and on average they required about $1,800,000 worth of steel girders. Table 6 summarizes the percentages of the U.S. national totals that resource inputs into manufacturing steel girders for 290,000 average bridges accounted for. Table 7 shows the percentages for environmental outputs. The largest percentage belongs to iron ore. If half of the U.S. bridges were steel, the iron ore consumption would amount to more than 5 years' aggregate national demand. Similarly, bauxite consumption would amount to 3 years', and coke consumption would amount to 2 years' U.S. demand. Building 290,000 new steel

TABLE 6. Resource Inputs for Manufacturing Steel Girders for 290,000 Average Bridges, as Percentage of Annual National Totals in the United States

Resource inputs (1)	For 290,000 bridges (2)	Annual national total (%) (3)
Electricity (kW·h million)	406,000	17
Coal and coke		
Anthracite coal (t)	406,000	9
Bituminous coal (t)	232,000,000	39
Coke (t)	29,000,000	239
Natural gas (t)	17,400,000	21
Liquefied natural gas (t)	1,450,000	7
Motor gasoline (t)	5,800,000	2
Aviation fuel (t)	58,000	2
Jet fuel (t)	2,030,000	4
Kerosene (t)	1,450	0.06
Light fuel oil (t)	14,500,000	12
Heavy fuel oil (t)	5,800,000	13
Liquefied petroleum gas (t)	2,900,000	10
Ores		
Iron ore (t)	261,000,000	548
Ferrous ore (dollars)	203,000,000	92
Copper ore (t)	72,500,000	36
Bauxite (t)	2,320,000	287
Gold ore (t)	72,500,000	81
Silver ore (t)	14,500,000	119
Lead-zinc ore (dollars)	87,000,000	33
Uranium-vanadium ore (dollars)	87,000,000	35
Fertilizers		
Ammonia (t)	580,000	6
Ammonium nitrate (t)	145,000	4
Ammonium sulfate (t)	11,600	0.6
Urea (t)	29,000	0.6
Organic fertilizers (t)	2,900	0.2
Superphosphate (t)	116,000	2
Phosphatic fertilizers (t)	290	0.2

Note: Resource inputs and corresponding national totals are based on 1987 data.

TABLE 7. Environmental Outputs for Manufacturing Steel Girders for 290,000 Average Bridges as Percentage of Annual National Totals in the United States

Environmental outputs (1)	For 290,000 bridges (2)	Annual national total (%) (3)
TRI air releases (t)	203,000	32
TRI water releases (t)	20,000	22
TRI land releases (t)	174,000	140
TRI underground releases (t)	58,000	43
TRI releases to environment (t)	290,000	30
TRI total releases and transfers (t)	2,030,000	83
CMU-ET for air releases (t H_2SO_4 equivalent)	87,000	64
CMU-ET for water releases (t H_2SO_4 equivalent)	14,500	70
CMU-ET for land releases (t H_2SO_4 equivalent)	870,000	109
CMU-ET for underground releases (t H_2SO_4 equivalent)	29,000	70
CMU-ET for total releases (t H_2SO_4 equivalent)	870,000	79
CMU-ET for releases and transfers (t H_2SO_4 equivalent)	5,800,000	66
Ozone depletion potential (t CFC-11 equivalent)	2,320	14
RCRA hazardous waste generated (t)	20,300,000	9
RCRA hazardous waste managed (t)	11,600,000	5
RCRA hazardous waste shipped (t)	8,700,000	55
SO_2 (t)	8,700,000	40
NO_x (t)	2,900,000	35
Methane (t)	14,500	40
VOC (t)	232,000	50

Note: Environmental outputs and corresponding national totals are based on 1993 data.

bridges in the United States would raise considerably environmental outputs as well. Since steel bridges in the United States have not been built in 1 year, but over many decades, the annualized input and output totals attributed to bridges would be small. The comparison to annual national totals is insightful as we do not regularly think of bridges as sinks of renewable and nonrenewable resources and direct and indirect causes of pollution.

CONCLUSIONS

When looking at the initial construction of equivalent bridge designs, steel-reinforced concrete girders appear to have lower overall environmental effects than steel girders. However, steel girders are reusable and recyclable at the end of their useful life. Steel superstructures have had a documented minimum reuse rate of 17% and a minimum recycle rate of 21%, based on a limited U.S. national survey (Bloomquist et al. 1993). For concrete girders, the options have mostly been limited to landfilling in the past. The reuse and recycle rates for steel girders presumably save input resources and reduce environmental pollution compared to using only virgin materials. Recycling rates for steel girders are taken into account in EIO-LCA through the current mix of raw materials for steel mills. In 1987, roughly 20–30% of steel was recycled. However, Malin (1997) reports that steel plates used to fabricate structural members are increasingly manufactured in minimills that use almost exclusively steel scrap in electric arc furnaces to produce steel. If we assume that the resource inputs and the environmental outputs are lower from minimills than from integrated mills with basic oxygen furnaces, then the results of this study are skewed against steel.

A summary of environmental effects assessed in this article is given in Table 8. Many other environmental burdens have not been included in this work due to the lack of data and, as in the case of visual impacts, the lack of an acceptable metric. For example, dust emissions, water usage, nonhazardous solid waste generation and disposal, generation and disposal of hazardous waste by type, environmental effects of landfills, noise and vibration, and visual impacts have not been assessed. If these (and other) environmental effects would have been included, our assessment might have yielded different conclusions. Also, the data used in this analysis have large uncertainties associated with them, and they reflect past economic and environmental performance. Therefore, a similar assessment using different designs and baseline years may yield different conclusions.

TABLE 8. Summary of Environmental Effects of Steel versus Steel-Reinforced Concrete Girders for Typical Highway Bridge

Type of girder (1)	Manufacturing (2)	Use (3)	End-of-life option (4)
Steel	Likely higher resource input requirements and environmental outputs	Paint, other maintenance	Better reuse and recyclability
Concrete	Better	Other maintenance	Mostly landfilling

If, however, obsolescence is a main problem, it might not matter if one material lasts longer than the other because a bridge might be decommissioned long before it fails structurally. If indeed this might be the case, bridges should be built from the material that has comparably the lowest environmental burdens. In particular applications, however, engineering, aesthetic, or economic criteria might outweigh the environmental factor.

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