Life-cycle Greenhouse Gas Emissions Associated with a Highway Reconstruction: A New Jersey Case Study

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Abstract

A comprehensive greenhouse gas (GHG) life-cycle analysis is conducted for a large highway reconstruction project in New Jersey. The GASCAP model is used to determine the total life-cycle GHG emissions associated with the materials used, construction equipment, mobilization of resources for the project, traffic disruption during construction, and materials used for life-cycle maintenance. The focus of the case study is to determine the relative share of these various components, as well as the importance of accounting for non-CO\textsubscript{2} GHG emissions. Results suggest that non-CO\textsubscript{2} emissions are substantial enough that they should be included and that various smaller material components, not just those associated with materials in the pavement should also be included. For this specific case-study, traffic disruption was a minor component of total emissions, though this result may differ depending on project and road network details. GHG emissions associated with this reconstruction project account for about 20\% of the total emissions expected to be generated from traffic using the highway over a 50 year lifetime.
Introduction

New Jersey’s Global Warming Response Plan (GWRP) seeks to significantly reduce carbon emissions by 2050. Within New Jersey, transportation associated emissions account for over 40% of total greenhouse gas (GHG) emissions. One of the specific action items listed within the plan is to “establish a carbon footprint standard for transportation projects” (1). This requires the assessment of the life-cycle GHG emissions associated with the construction and maintenance of transportation projects.

The Greenhouse Gas Assessment Spreadsheet for Transportation Capital Projects (or GASCAP) model \(^1\) was developed with this in mind (2, 3). The model permits an analysis of project life-cycle greenhouse gas (GHG) emissions, including direct and upstream estimates for CO\(_2\), CH\(_4\), N\(_2\)O, HFC, and SF\(_6\), as well as providing estimates of the combined global warming potential. One objective is to allow engineering staff to design and stage project construction to minimize life-cycle GHG emissions. This paper summarizes the analysis of a major road reconstruction project, reconstruction of a four lane arterial (two lanes in each direction) state highway, located on a barrier Island in Ocean County, NJ, that was extensively damaged by Hurricane Sandy.

The GASCAP model includes components to estimate the upstream and direct emissions from each phase of the construction and maintenance of highway projects. These include the emissions associated with construction materials, construction equipment, project mobilization, traffic disruption during construction, and life-cycle maintenance activities. Upstream life-cycle emissions for all components are derived primarily from the GREET model.(4, 5)

The primary materials used in construction projects are asphalt, concrete, and steel. Emissions from asphalt are sensitive to the heating input and the energy and emissions are derived from a heating model (6). Smaller construction components, such as materials for drainage, culverts, pipes, and other minor items are contained in project bid-sheets which define the detailed inputs for projects. A procedure to input this information is an integral part of the GASCAP model.

Construction equipment emissions are derived from EPA’s NONROAD model (7) and assumptions on project-specific equipment activity are drawn from activity logs based on California data (8).

GASCAP also includes a module for estimating emissions from project mobilization. This provides estimates for moving materials, equipment, and labor to a jobsite, as well as lighting for night work, if needed. How the project is staged is also a potential source of emissions; if the road must be closed to traffic, then diversions will likely generate additional emissions from the vehicles that use the road, compared to when the road is fully open. The model includes methods to evaluate the emissions associated with delayed and diverted traffic, based on traffic flow assumptions derived from the Highway

\(^{1}\) The model is available for download at www.gascap.org
Capacity Manual (9) and emissions for on-road vehicles estimated using EPA’s MOVES model (10). Staging is one way that a state transportation agency might have substantial control over the emissions that are generated from construction and maintenance activities.

An additional issue is the maintenance of a road over its lifetime. In theory, transportation agencies should implement an optimal maintenance strategy that minimizes costs and keeps a road surface in a state of good repair. This involves a set schedule of seal cracking, pothole filling, and milling and repaving the surface, typically over about a 50 year lifetime. As an example, Pennsylvania provides published guidance on life-cycle maintenance procedures (11). The GASCAP model uses similar procedures developed for New Jersey (3), and accounts for the emissions associated with the materials used and the equipment used during maintenance activities over a 50 year schedule of activities. Retirement and deconstruction of the road is assumed not to occur, although at the 50 year mark, it is assumed that major reconstruction would occur, but this is not accounted for in the analysis.

The GASCAP model provides a template for analysis that is substantially more sophisticated than earlier work in this area. The PaLATE model, developed in California, was one of the first attempts to estimate life-cycle emissions associated with road construction (12). The model estimated CO₂ emissions associated with the main materials used in roads, primarily concrete and asphalt pavement, base, and the fill components for sub-base. It also included methods to account for disposal and recycling of materials and their use as fill materials. PaLATE is somewhat limited in that its scope does not include other GHGs and does not include many of the other components of road construction.

Defining the boundary of any life-cycle assessment determines both its broad applicability and the scope of the assessment. In any road construction project there are both minor components and much larger factors that typically generate the bulk of the emissions associated with the project. A framework for defining system boundaries was devised by (13), that includes the following components: material extraction and production, transportation to site, onsite equipment activity, disruption to traffic from project work, carbonation, lighting, albedo, and rolling resistance associated with the smoothness of the road. The approach used in GASCAP includes most of these components, but also some additional ones; and our focus is to assess the relative contribution of each in a full life-cycle analysis.

Among the components listed by (13), we do not include an assessment of changes in rolling resistance, that is how deterioration of the road surface may affect GHG emissions associated with usage of the road over its lifetime. A review of other pavement life-cycle analysis studies found that most did not include this component (14). Recent work has attempted to evaluate the impact of road deterioration and found it to be a substantial component of emissions (15, 16), and (17). The main issue is how maintenance procedures can prevent deterioration of the road surface such that vehicle fuel economy is not degraded. We do, however, provide a rough estimate of
total GHG emissions associated with usage of the road, in order to determine the relative importance of examining emissions associated with construction.

We also do not assess the albedo impacts (i.e., relative reflectivity of the pavement surface and how this may contribute to additional warming of the atmosphere, depending on pavement characteristics) (18). There is still uncertainty about the ability to capture adequate information to fully model the effects of emissions (19).

This paper summarizes the first application of GASCAP. The primary objective was to determine what components of a road reconstruction project account for the largest share of life-cycle GHG emissions and to determine the primary points at which a state transportation agency can change procedures to minimize GHG emissions. Much of the previous work on life cycle analysis has examined different pavements, mainly asphalt versus concrete (14); we only examine asphalt pavement, but focus on the relative importance of various components of the analysis and how this relates to the GHG emissions from the vehicles using the road.

The case study analyzed is a large road reconstruction (NJ Rte. 35). The bulk of emissions are associated with direct and upstream material components used in the road project. Many of the smaller components used on the project, when added together add non-trivial emissions to the project. Equipment emissions are a minor component. The main finding is that it is mainly the embodied emissions associated with materials that account for most emissions thus limiting the ability of a transportation agency to influence the GHG emissions of most projects. Emissions associated with disruption from traffic were minor in this case study, but might be more significant if major diversions are required. Our analysis also found that total life-cycle emissions from building the road are a substantial component compared to the emissions that are generated from vehicles using the road.

**Road Reconstruction: NJ Route 35**

The case study focused on a large reconstruction project involving the restoration of damage caused by Superstorm Sandy to Route 35 from Berkley Township to Toms River Township, in Ocean County New Jersey. NJDOT Contract No. 13130 is one of three federally funded projects to repair storm damage to Route 35, and served as the basis for our case study. This project is located between Mile Posts 0 and 4 from Berkley Township to Toms River Township, and is an arterial highway with two-lanes in both directions with a wide shoulder. The project includes grading, pavement, drainage, and sign structures in four municipalities. The successful bid on this contract was $80.7 million. The contract was let June 13, 2013 and is scheduled for completion October 1, 2015. The approximate location of the site is shown in Figure 1.

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2 The New Jersey Department of Transportation lists all information associated with contract bids at: [http://www.state.nj.us/transportation/business/procurement/ConstrServ/awards13.shtm](http://www.state.nj.us/transportation/business/procurement/ConstrServ/awards13.shtm). This provides detail on contract 13130 that served as the basis for much of the data input for this case study.
Assumptions

In assessing the GHG emissions, various assumptions were required, mainly due to lack of data on various elements of the project. These were generally minor and did not affect the overall conclusions concerning the comparison of sources of emissions, but certainly would have an impact on the total emissions, although the relative magnitude would be small.

Any road construction project involves a variety of ancillary items, mainly associated with drainage systems, but also for signage and electrical fixtures. These are not typically included in pavement life-cycle analysis models. An assessment was made of how many of the corresponding bid sheet item codes were available in GASCAP; about 25% were missing, likely due to these being continually updated and not being available at the time the model was coded. About 9% of the items were temporary items, not
included within the scope of the GASCAP model, for example construction layouts, monuments, pavement markings, drums, cofferdams, barricades, crash cushions, and fencing. While some of these items have significant mass they are largely reusable. In sum, the assessment of the other material components suggests that these missing and omitted items would be a relatively minor component of the total emissions estimate.

Details on how the project was to be staged were not available. Thus, since this part of Route 35 is the only arterial running through a barrier island, it is assumed that it may be either closed or restricted along the section’s length. This potentially affects the realism of the estimates associated with the traffic disruption component of the model. It was assumed that the reconstructed road will have a 50 year lifetime. The life-cycle maintenance module did not include additional estimates of future traffic disruption.

Emissions Associated with Materials

The major materials used in a road construction project are asphalt pavement, concrete (including reinforced concrete), and steel. A breakdown of GHG emissions in metric tons (MT) by material type, assuming hot mix asphalt heated to 325° F is shown in Table 1 and this is graphically displayed in Figure 2. Both upstream and direct CO₂e emissions are shown; heating and placement of the asphalt causes direct emissions. Asphalt accounts for a majority (57%) of CO₂e emissions and upstream asphalt emissions (40%) are the largest single component of material emissions. Concrete, including reinforced concrete and mixed materials, accounts for the second largest component of CO₂e emissions. Many mixed materials include large amounts of reinforced concrete. Structural steel accounts for roughly 7% of CO₂e, excluding the portion used in mixed materials. The other materials are a minor source of emissions.
Table 1 - Material emissions for different components (NJDOT bid sheet 13130)

<table>
<thead>
<tr>
<th>By Material</th>
<th>Count</th>
<th>Upstream CO$_2$e</th>
<th>Direct CO$_2$e</th>
<th>Total CO$_2$e</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aggregate</td>
<td>4</td>
<td>326.1 1.22%</td>
<td>0.0 0.00%</td>
<td>326.1 1.22%</td>
</tr>
<tr>
<td>Aluminum</td>
<td>3</td>
<td>271.6 1.02%</td>
<td>0.0 0.00%</td>
<td>271.6 1.02%</td>
</tr>
<tr>
<td>Asphalt</td>
<td>12</td>
<td>10,753.0 40.36%</td>
<td>4,487.1 16.84%</td>
<td>15,240.0 57.21%</td>
</tr>
<tr>
<td>Binder</td>
<td>3</td>
<td>259.4 0.97%</td>
<td>312.2 1.17%</td>
<td>571.6 2.15%</td>
</tr>
<tr>
<td>Concrete</td>
<td>14</td>
<td>2,798.9 10.51%</td>
<td>0.0 0.00%</td>
<td>2,798.9 10.51%</td>
</tr>
<tr>
<td>Metal</td>
<td>8</td>
<td>28.9 0.11%</td>
<td>0.0 0.00%</td>
<td>28.9 0.11%</td>
</tr>
<tr>
<td>Mixed</td>
<td>18</td>
<td>4,560.8 17.12%</td>
<td>0.0 0.00%</td>
<td>4,560.8 17.12%</td>
</tr>
<tr>
<td>Other</td>
<td>5</td>
<td>33.6 0.13%</td>
<td>0.0 0.00%</td>
<td>33.6 0.13%</td>
</tr>
<tr>
<td>Reinforced Concrete</td>
<td>10</td>
<td>1,042.5 3.91%</td>
<td>0.0 0.00%</td>
<td>1,042.5 3.91%</td>
</tr>
<tr>
<td>Steel/Iron</td>
<td>28</td>
<td>1,764.2 6.62%</td>
<td>0.0 0.00%</td>
<td>1,764.2 6.62%</td>
</tr>
<tr>
<td>Wire</td>
<td>10</td>
<td>1.5 0.01%</td>
<td>0.0 0.00%</td>
<td>1.5 0.01%</td>
</tr>
<tr>
<td>Total</td>
<td>115</td>
<td>21,840.4 81.98%</td>
<td>4,799.3 18.02%</td>
<td>26,639.7 100.00%</td>
</tr>
</tbody>
</table>

Figure 2. Material Emissions (CO$_2$e) for different components (NJDOT bid sheet 13130)

Table 2 displays the GHG emissions for the different material components used in construction, corresponding to specific item code sections in the bid sheets. The proportional contribution of each of the materials to GHG emissions is displayed graphically in Figure 3. Hot mix asphalt accounts for most (54%) of the emissions.
Considerable effort went into modeling the next three components, drainage structures, pipes, and curbs, which together include 32 items and account for roughly 31% of material emissions. Aggregate base courses, sidewalks, driveways, islands, and non-vegetative surfaces account for another 10% of GHG emissions from eight items. Utility items, including water and sewer, account for about 2% of GHG emissions from 10 items. About 1% of GHG emissions are from traffic signals, which probably have a substantial number of item codes not included in GASCAP, but these are likely minor. The remaining nine item code categories account for another 1% of emissions from 37 items listed in the contract. These include traffic control devices, soil and stone for embankments, structural concrete, signs and support structures and electrical items other than traffic signals. As mentioned previously, there are various omissions to these items, but given that the smaller items account for a small fraction of material GHG emissions, this is a minor omission.

Table 2 - Material emissions for each section of bid sheet items (NJDOT bid sheet 13130)

<table>
<thead>
<tr>
<th>By Item Code Section</th>
<th>Count</th>
<th>Upstream CO(_2)e</th>
<th>Direct CO(_2)e</th>
<th>Total CO(_2)e</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hot Mix Asphalt (HMA) Courses (401)</td>
<td>9</td>
<td>9,498.7</td>
<td>4,764.3</td>
<td>14,263.0</td>
</tr>
<tr>
<td>Drainage Structures (602)</td>
<td>15</td>
<td>4,418.5</td>
<td>0.0</td>
<td>4,418.5</td>
</tr>
<tr>
<td>Pipe (601)</td>
<td>16</td>
<td>2,072.7</td>
<td>0.0</td>
<td>2,072.7</td>
</tr>
<tr>
<td>Curb (607)</td>
<td>1</td>
<td>1,784.4</td>
<td>0.0</td>
<td>1,784.4</td>
</tr>
<tr>
<td>Aggregate Base Course (302)</td>
<td>3</td>
<td>1,701.1</td>
<td>0.0</td>
<td>1,701.1</td>
</tr>
<tr>
<td>Sidewalks, Driveways, and Islands (606)</td>
<td>5</td>
<td>796.2</td>
<td>3.7</td>
<td>799.9</td>
</tr>
<tr>
<td>Traffic Signals (702)</td>
<td>11</td>
<td>382.5</td>
<td>0.0</td>
<td>382.5</td>
</tr>
<tr>
<td>Water Utility (651)</td>
<td>6</td>
<td>318.1</td>
<td>0.0</td>
<td>318.1</td>
</tr>
<tr>
<td>Beam Guide Rail (609)</td>
<td>6</td>
<td>229.3</td>
<td>0.0</td>
<td>229.3</td>
</tr>
<tr>
<td>Concrete (903)</td>
<td>1</td>
<td>186.5</td>
<td>0.0</td>
<td>186.5</td>
</tr>
<tr>
<td>Sanitary Sewers (652)</td>
<td>4</td>
<td>170.1</td>
<td>0.0</td>
<td>170.1</td>
</tr>
<tr>
<td>Non-Vegetative Surfaces (608)</td>
<td>1</td>
<td>50.5</td>
<td>25.4</td>
<td>75.9</td>
</tr>
<tr>
<td>Other</td>
<td>37</td>
<td>231.9</td>
<td>5.9</td>
<td>237.8</td>
</tr>
<tr>
<td>Total</td>
<td>115</td>
<td>21,840.4</td>
<td>4,799.3</td>
<td>26,639.7</td>
</tr>
</tbody>
</table>
GASCAP was designed to model CO₂, CH₄, N₂O, HFC, and SF₆ as well as the oxidation of CO to CO₂. Table 3 provides a decomposition of the different GHG emissions associated with materials in CO₂e units, assuming carbon equivalence factors as reported in (20). No HFC emissions are shown for materials, as these are only estimated for direct construction equipment emissions, not for emissions associated with materials. Not surprisingly, CO₂ emissions account for nearly all (99.5%) of direct materials emissions but somewhat less (86.2%) of the upstream emissions. Less than one fifth (18%) of total emissions from materials are direct emissions. These are mostly from asphalt heating and placement. Total emissions are mostly CO₂, but limiting GHG emissions to CO₂ results in an undercount of total GHG emissions by about 13%. SF₆ in this case is not a major contributor to total GHG emissions.

<table>
<thead>
<tr>
<th></th>
<th>Direct MT CO₂e</th>
<th>Upstream MT CO₂e</th>
<th>Total MT CO₂e</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO₂</td>
<td>4,774.8</td>
<td>18,831.3</td>
<td>23,606.0</td>
</tr>
<tr>
<td>CH₄</td>
<td>4.4</td>
<td>2,094.8</td>
<td>2,099.2</td>
</tr>
<tr>
<td>N₂O</td>
<td>20.2</td>
<td>867.5</td>
<td>887.7</td>
</tr>
<tr>
<td>SF₆</td>
<td>0.0</td>
<td>46.8</td>
<td>46.8</td>
</tr>
<tr>
<td>Total</td>
<td>4,799.3</td>
<td>21,840.4</td>
<td>26,639.7</td>
</tr>
</tbody>
</table>
Construction Equipment Emissions

The estimation of emissions from construction equipment requires information on both the activity of the equipment used on a project and emissions factors for specific types of equipment. The latter is readily available via EPA's NONROAD model, and emissions factors are included in the GASCAP model. Information on the details of equipment activity associated with any specific project is not available. California data was used to estimate activity for various components of the project. (8) collected equipment activity data for six types of projects in California, including detail on the various phases of each project, ranging from land clearance, roadway excavation, to paving and striping of the road surface (8). To our knowledge, this is the only data available that can be broadly applied to other similar projects.

To best approximate the equipment activity, three types of project activities were modeled. These were equivalent to freeway construction, landscaping, and median installation, as defined in (8). The proportion and hours of work for the various phases of each of these activities are shown in Table 4. The number of total workdays for each activity was assumed to be 420 days for freeway construction, 50 days for landscaping, and 20 days for median installation. The latter activity was the best approximation available to estimate equipment activity associated with signage installation, which is a major phase of median construction activity. Each of the phases of work assumed a specific distribution of equipment types (details are available in (21) tables 29-31). In addition it was assumed that two 300 hp diesel generators would be used for 300 hours each over the duration of the project (primarily to allow project work at night).

### Table 4. Route 35 Reconstruction Equipment Activity Assumptions

<table>
<thead>
<tr>
<th>Sections 0001 and 0003 Roadway Activity</th>
<th>Proportion of work</th>
<th>Average hours/day</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 - Land Clearing and Grubbing</td>
<td>2.0%</td>
<td>1.3</td>
</tr>
<tr>
<td>2 - Roadway Excavation</td>
<td>12.8%</td>
<td>8.2</td>
</tr>
<tr>
<td>3 - Structural Excavation</td>
<td>1.9%</td>
<td>1.2</td>
</tr>
<tr>
<td>4 - Base and Subbase</td>
<td>10.4%</td>
<td>6.7</td>
</tr>
<tr>
<td>5 - Structural Concrete</td>
<td>8.7%</td>
<td>5.6</td>
</tr>
<tr>
<td>6 – Paving</td>
<td>13.8%</td>
<td>8.9</td>
</tr>
<tr>
<td>7 - Drainage / Environmental / Landscaping</td>
<td>9.9%</td>
<td>6.4</td>
</tr>
<tr>
<td>8 - Striping / Painting</td>
<td>1.2%</td>
<td>0.8</td>
</tr>
<tr>
<td>9 - Traffic Control / Signage / Barriers</td>
<td>24.2%</td>
<td>15.6</td>
</tr>
<tr>
<td>10 - Change Contract Orders</td>
<td>10.9%</td>
<td>7.0</td>
</tr>
<tr>
<td>11 – Other</td>
<td>4.2%</td>
<td>2.7</td>
</tr>
<tr>
<td>TOTAL</td>
<td>100.0%</td>
<td>64.4</td>
</tr>
</tbody>
</table>
Section 0006 Landscaping

<table>
<thead>
<tr>
<th>Activity</th>
<th>Proportion of work</th>
<th>Average hours/day</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 - Land Clearing and Grubbing</td>
<td>1.2%</td>
<td>0.0</td>
</tr>
<tr>
<td>2 - Roadway Excavation</td>
<td>0.1%</td>
<td>0.0</td>
</tr>
<tr>
<td>3 - Structural Excavation</td>
<td>0.0%</td>
<td>0.0</td>
</tr>
<tr>
<td>4 - Base and Subbase</td>
<td>2.0%</td>
<td>0.1</td>
</tr>
<tr>
<td>5 - Structural Concrete</td>
<td>0.0%</td>
<td>0.0</td>
</tr>
<tr>
<td>6 – Paving</td>
<td>0.0%</td>
<td>0.0</td>
</tr>
<tr>
<td>7 - Drainage / Environmental / Landscaping</td>
<td>82.0%</td>
<td>2.3</td>
</tr>
<tr>
<td>8 - Striping / Painting</td>
<td>0.0%</td>
<td>0.0</td>
</tr>
<tr>
<td>9 - Traffic Control / Signage / Barriers</td>
<td>0.4%</td>
<td>0.0</td>
</tr>
<tr>
<td>10 - Change Contract Orders</td>
<td>4.1%</td>
<td>0.1</td>
</tr>
<tr>
<td>11 – Other</td>
<td>10.2%</td>
<td>0.3</td>
</tr>
<tr>
<td><strong>TOTAL</strong></td>
<td>100.0%</td>
<td>2.8</td>
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Sections 0007 and 0008 Sign (Median) Installation

<table>
<thead>
<tr>
<th>Activity</th>
<th>Proportion of work</th>
<th>Average hours/day</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 - Land Clearing and Grubbing</td>
<td>0.0%</td>
<td>0.0</td>
</tr>
<tr>
<td>2 - Roadway Excavation</td>
<td>12.6%</td>
<td>5.1</td>
</tr>
<tr>
<td>3 - Structural Excavation</td>
<td>0.0%</td>
<td>0.0</td>
</tr>
<tr>
<td>4 - Base and Subbase</td>
<td>5.3%</td>
<td>2.1</td>
</tr>
<tr>
<td>5 - Structural Concrete</td>
<td>0.0%</td>
<td>0.0</td>
</tr>
<tr>
<td>6 – Paving</td>
<td>6.2%</td>
<td>2.5</td>
</tr>
<tr>
<td>7 - Drainage / Environmental / Landscaping</td>
<td>0.1%</td>
<td>0.0</td>
</tr>
<tr>
<td>8 - Striping / Painting</td>
<td>0.6%</td>
<td>0.2</td>
</tr>
<tr>
<td>9 - Traffic Control / Signage / Barriers</td>
<td>67.9%</td>
<td>27.3</td>
</tr>
<tr>
<td>10 - Change Contract Orders</td>
<td>2.2%</td>
<td>0.9</td>
</tr>
<tr>
<td>11 – Other</td>
<td>4.9%</td>
<td>2.0</td>
</tr>
<tr>
<td><strong>TOTAL</strong></td>
<td>99.8%</td>
<td>40.1</td>
</tr>
</tbody>
</table>

Project Lighting

<table>
<thead>
<tr>
<th>Activity</th>
<th>HP</th>
<th>Total hours</th>
</tr>
</thead>
<tbody>
<tr>
<td>Generator</td>
<td>300</td>
<td>600</td>
</tr>
</tbody>
</table>

Total GHG emissions from the equipment used are shown in Table 5. As with materials, CO₂ accounts for 99.5% of all direct GHG emissions. CH₄, however, accounts for a full third (33.6%) of the total CO₂e of upstream fuel emissions, due mainly to fugitive emissions during refinement. Overall the relative contribution of non-CO₂ GHG species (6.9%) to total emissions is somewhat smaller than that of materials emissions (11.4%). The contribution of SF₆ is roughly the same. Equipment was modeled assuming no air...
conditioning, thus these results do not show HFC emissions. Black carbon (PMBC) emissions are also shown as a small component of equipment emissions but cannot be added to the totals as there is no conversion to CO₂e emissions.

<table>
<thead>
<tr>
<th></th>
<th>Direct MT CO₂e</th>
<th>Upstream MT CO₂e</th>
<th>Total MT CO₂e</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO₂</td>
<td>757.4</td>
<td>111.6</td>
<td>869.0</td>
</tr>
<tr>
<td>CH₄</td>
<td>0.9</td>
<td>57.9</td>
<td>58.7</td>
</tr>
<tr>
<td>N₂O</td>
<td>2.8</td>
<td>0.8</td>
<td>3.6</td>
</tr>
<tr>
<td>SF₆</td>
<td>0.0</td>
<td>1.9</td>
<td>1.9</td>
</tr>
<tr>
<td>Total</td>
<td>761.1</td>
<td>172.1</td>
<td>933.2</td>
</tr>
</tbody>
</table>

As a check on our equipment emissions estimates, total fuel consumption for the project was also calculated. Results are shown in Table 6. Fuel use suggests that the procedure used to estimate equipment usage is reasonable (about 20% of this total is due to construction equipment used on the project site, while the remainder is for mobilization of resources to the site). The cost of this quantity of fuel is less than 4% of the total project budget. As will be shown below, the net contribution of equipment emissions to the total project GHG emissions is small, thus any errors in the assumptions used to estimate equipment emissions would have little impact on the total emissions for the project.

<table>
<thead>
<tr>
<th>Fuel Used</th>
<th>Quantity (gallons)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gasoline (10% Ethanol RFG)</td>
<td>20,635.25</td>
</tr>
<tr>
<td>Gasoline</td>
<td>313.53</td>
</tr>
<tr>
<td>Diesel</td>
<td>490,736.43</td>
</tr>
</tbody>
</table>

Emissions from Life-cycle Maintenance

Emissions associated with life-cycle maintenance activities are based on a maintenance plan developed from the engineering expertise of NJ DOT engineers (3), Table 4. Emissions estimates are derived for the materials used and the equipment used on site, but equipment emissions from mobilization activities are not included; these latter would generally be minor compared to the resources needed to mobilize for major
reconstruction. Likewise, the maintenance emissions do not include any vehicle emissions associated with road closures or vehicle disruptions and diversions.

Input data on the dimensions of the road and the pavement surface are needed to estimate maintenance emissions. The project is being conducted over four miles and the road is two lanes in each direction of standard width with wide shoulders on both sides. The default width of 12 feet per lane was assumed. The shoulders appear to be slightly narrower so shoulder width is assumed to be 10 feet per side or 20 feet for both sides. Pavement depth is assumed to be eight inches and shoulder depth is assumed to be two inches.

Table 7 displays the relative projected emissions of life cycle maintenance activities for 50 years. The global warming impact of upstream emissions is slightly more than twice that of direct emissions. Virtually all of the direct global warming impact is attributable to CO₂. As these combine emissions over a 50 year maintenance cycle, the estimates do not capture efficiency improvements in potential upstream process emissions for the materials used. For example, electricity emissions associated with refining processes would presumably be less carbon intensive in 50 years compared to the present; however this analysis assumes no change in the upstream processes. A difficulty with life-cycle analysis over this type of time frame is the uncertainty associated with technology changes (19).

<table>
<thead>
<tr>
<th></th>
<th>Direct MT CO₂e</th>
<th>Upstream MT CO₂e</th>
<th>Total MT CO₂e</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO₂</td>
<td>993.3</td>
<td>2,041.8</td>
<td>3,035.2</td>
</tr>
<tr>
<td>CH₄</td>
<td>1.3</td>
<td>455.0</td>
<td>456.2</td>
</tr>
<tr>
<td>N₂O</td>
<td>4.2</td>
<td>9.0</td>
<td>13.3</td>
</tr>
<tr>
<td>SF₆</td>
<td>0.0</td>
<td>2.6</td>
<td>2.6</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>998.8</strong></td>
<td><strong>2,508.4</strong></td>
<td><strong>3,507.2</strong></td>
</tr>
</tbody>
</table>

**Mobilization**

Mobilization involves the movement of both resources and personnel to a worksite. Data is not available on how many vehicles are actually used on this project, however, various estimates can be made based on the quantity of materials itemized in the bid sheets. From this total miles traveled can be estimated using assumptions about where the resources are moving from. Emissions factors for on-road vehicles are derived from EPA’s MOVES model.
For this case study the distances are not varied to avoid introduction of arbitrary systematic errors. Equipment is assumed to come from and return to a central facility 20 miles from the construction site. Materials come from a simplified hypothetical list of vendors between 14.5 and 16.0 miles from the construction site. Small items are transported with pickup trucks. Loose materials are transported using dump trucks. Short haul trucks were assumed for all other materials. Large materials were assigned combination trucks. The number of loads was estimated assuming 30 tons per load, for the larger trucks. Volumetric measures reported in the bid sheets were converted to tons based on density. Where this method was not adequate the number of trips was estimated subjectively. The corresponding assumptions for number of one-way trips and vehicle miles traveled are shown in Table 8.

Air conditioning was assumed for all vehicles. Estimates of HFC leakage from air conditioning are not associated with the travel distance of vehicles, rather they are based on the time the vehicle is used. These were calculated assuming the vehicles are used for the entire period of the project, which may be an overestimate as this assumes the vehicles are not used for any other purpose.

Table 9 shows that direct emissions from mobilization activities account for just over 80% of emissions excluding project lighting. As in the other modules direct emissions are the major source of CO₂ (>99.5%). A large majority of upstream CO₂e (88%) is from CO₂. CH₄ and N₂O account for 14.3% and 0.5% of CO₂e, respectively. Direct HFC fugitive emissions account for 0.1% of CO₂e; this may even be an overestimation as we assume air conditioners are used in all vehicles. Other GHG species contribute little. CO₂ accounts for 97% of combined CO₂e and CH₄ accounts for nearly all of the balance.
Table 9 - Mobilization emissions by GHG species

<table>
<thead>
<tr>
<th></th>
<th>Direct MT CO$_2$e</th>
<th>Upstream MT CO$_2$e</th>
<th>Total MT CO$_2$e</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO$_2$</td>
<td>3,065.5</td>
<td>622.6</td>
<td>3,688.0</td>
</tr>
<tr>
<td>CH$_4$</td>
<td>0.3</td>
<td>105.2</td>
<td>105.5</td>
</tr>
<tr>
<td>N$_2$O</td>
<td>2.0</td>
<td>3.9</td>
<td>5.9</td>
</tr>
<tr>
<td>SF$_6$</td>
<td>0.0</td>
<td>2.7</td>
<td>2.7</td>
</tr>
<tr>
<td>HFC</td>
<td>2.3</td>
<td>0.0</td>
<td>2.3</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>3,070.1</strong></td>
<td><strong>734.327</strong></td>
<td><strong>3804.409</strong></td>
</tr>
</tbody>
</table>

Traffic Disruption

The disruption to traffic during the project work is a source of additional emissions. The GASCAP model allows various work zone staging scenarios to be analyzed, ranging from just setting up a work zone along the highway, to diverting traffic on to alternate routes. Estimates of VMT and changes in traffic speeds are based on the Highway Capacity Manual (9), and emissions determined using emissions factors from EPA’s MOVES model.

For this case study it was assumed that there was a single lane closure over the 762 day projected span of the project work. To estimate the delay to traffic, and subsequent impacts on emissions, road design data are needed as inputs. The area being reconstructed is between Mile Posts 0 and 4, where Route 35 is an arterial with two lanes in both directions. The average annual daily traffic (AADT) for this segment is 8,467 vehicles; we assume 5 percent of these are trucks and buses, and the directional split is 53.125% for the dominant direction and 46.875% for the opposing direction (based on defaults for New Jersey in the MOVES model). Based on data from the NJDOT Straight Line Diagrams, lane widths are 12 feet or greater for the length of the observed part of this facility, the average posted speed limit is 32 mph, and there are 24 intersections along the four-mile length of road, so that on average there are six intersections per mile and there is no median (22). The grade is level, and the area is urban.

For a non-intermittent closure of one lane in both directions, added GHG emissions were calculated as shown in Table 10. Emissions are estimated to be about 1.1 MT of CO$_2$e. Other GHG emissions are minor. As with the mobilization scenario, the global warming of direct emissions is roughly four times that of upstream emissions. Thus, for this specific case study, these emissions are a minor component of the total project-related GHG emissions.
Table 10 - Traffic disruption emissions from closing one lane of traffic by GHG species

<table>
<thead>
<tr>
<th></th>
<th>Direct MT CO₂e</th>
<th>Upstream MT CO₂e</th>
<th>Total MT CO₂e</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO₂</td>
<td>0.8</td>
<td>0.2</td>
<td>1.0</td>
</tr>
<tr>
<td></td>
<td>99.55%</td>
<td>83.08%</td>
<td>96.04%</td>
</tr>
<tr>
<td>CH₄</td>
<td>&lt;0.1</td>
<td>&lt;0.1</td>
<td>&lt;0.1</td>
</tr>
<tr>
<td></td>
<td>0.03%</td>
<td>16.13%</td>
<td>3.47%</td>
</tr>
<tr>
<td>N₂O</td>
<td>&lt;0.1</td>
<td>&lt;0.1</td>
<td>&lt;0.1</td>
</tr>
<tr>
<td></td>
<td>0.41%</td>
<td>0.65%</td>
<td>0.46%</td>
</tr>
<tr>
<td>SF₆</td>
<td>0</td>
<td>&lt;0.1</td>
<td>&lt;0.1</td>
</tr>
<tr>
<td></td>
<td>0.00%</td>
<td>0.14%</td>
<td>0.03%</td>
</tr>
<tr>
<td>Total</td>
<td>0.9</td>
<td>0.2</td>
<td>1.1</td>
</tr>
<tr>
<td></td>
<td>100.00%</td>
<td>100.00%</td>
<td>100.00%</td>
</tr>
</tbody>
</table>

**Table 10 - Traffic disruption emissions from closing one lane of traffic by GHG species**

**Table 11 - Total emissions by GHG species, route 35 reconstruction case study**

<table>
<thead>
<tr>
<th></th>
<th>Direct MT CO₂e</th>
<th>Upstream MT CO₂e</th>
<th>Total MT CO₂e</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO₂</td>
<td>9,591.9</td>
<td>21,607.4</td>
<td>31,199.3</td>
</tr>
<tr>
<td></td>
<td>99.60%</td>
<td>85.56%</td>
<td>89.43%</td>
</tr>
<tr>
<td>CH₄</td>
<td>6.8</td>
<td>2,712.9</td>
<td>2,719.7</td>
</tr>
<tr>
<td></td>
<td>0.07%</td>
<td>10.74%</td>
<td>7.80%</td>
</tr>
<tr>
<td>N₂O</td>
<td>29.2</td>
<td>881.2</td>
<td>910.4</td>
</tr>
<tr>
<td></td>
<td>0.30%</td>
<td>3.49%</td>
<td>2.61%</td>
</tr>
<tr>
<td>SF₆</td>
<td>0.0</td>
<td>53.4</td>
<td>53.4</td>
</tr>
<tr>
<td></td>
<td>0.00%</td>
<td>0.21%</td>
<td>0.15%</td>
</tr>
<tr>
<td>HFC (CO₂e)</td>
<td>2.3</td>
<td>0.00%</td>
<td>2.3</td>
</tr>
<tr>
<td></td>
<td>0.00%</td>
<td>0.00%</td>
<td>0.01%</td>
</tr>
<tr>
<td>Total</td>
<td>9,630.2</td>
<td>25,254.9</td>
<td>34,885.1</td>
</tr>
<tr>
<td></td>
<td>100.00%</td>
<td>100.00%</td>
<td>100.00%</td>
</tr>
</tbody>
</table>
cycle maintenance (10%) and mobilization (11%). Equipment emissions account for only 3% of GHG emissions. Traffic disruption makes a trivial contribution to total emissions, at least for this case study.

Table 12 - GHG emissions from each component of the construction process

<table>
<thead>
<tr>
<th>Hot Mix</th>
<th>Emissions in MT CO₂e</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Upstream</td>
</tr>
<tr>
<td>Materials</td>
<td>21,840.4</td>
</tr>
<tr>
<td>Equipment</td>
<td>172.0</td>
</tr>
<tr>
<td>Maintenance</td>
<td>2,508.4</td>
</tr>
<tr>
<td>Mobilization</td>
<td>3,070.1</td>
</tr>
<tr>
<td>Traffic Disruption</td>
<td>0.9</td>
</tr>
<tr>
<td>Total</td>
<td>27,591.7</td>
</tr>
</tbody>
</table>

A related question is how these estimates compare to the emissions associated with using the road. A rough estimate of the carbon emissions from using the road over a 50 year lifetime gives an estimate of 140,152 MT of CO₂. This estimate assumes the same proportion of truck traffic (5%) and that there is no growth in AADT over the base year. Vehicle efficiency improves over this time frame and we use estimates derived from the VISION model (23). This model includes estimates based on the Annual Energy Outlook for 2013 (24); these incorporate the latest estimates of the impact of Corporate Average Fuel Economy standards on vehicle emissions and also include upstream emissions from fuel production. As we don't know the mix of heavy duty trucks using the road, we assume a flat (and liberal) estimate of 9 miles per gallon for all trucks. Thus, the 34,885 MT estimate associated with construction of the road is roughly 20% of the total emissions that one can attribute to both construction and use of the road over a 50 year lifetime.

Conclusions

This case study was intended to demonstrate the feasibility of conducting a life-cycle GHG emissions analysis of a large highway reconstruction project and to determine what the major components of GHG emissions are. The focus was on a four mile segment of route 35 in Ocean County, New Jersey, an $80 million project to repair a major arterial damaged by Hurricane Sandy.

Upstream emissions embedded within the materials used in the project account for the bulk of life-cycle GHG emissions, suggesting that choice of materials used in a project is a major consideration for reducing GHG emissions. Equipment GHG emissions are a minor component. Our estimates of equipment emissions, based on various default assumptions, appear reasonable, but are limited by not having actual construction
equipment activity data; thus our analysis is based on data collected in California. Emissions from mobilization account for about 10% of total project emissions; again, better data on the distance that resources and personnel are moved to a site can provide better estimates of this component of the analysis. For this particular case study, traffic disruption from closing a traffic lane during construction was a minor component. This may not always be the case, and another case study analyzed found that diverting traffic onto a detour can account for about 25% of project emissions (3).

Life-cycle maintenance is an important source of emissions, primarily from the materials used in maintaining the road surface, and potentially from traffic disruption during maintenance activities, although this was not estimated for this case study. Improvements to the modeling could be made by evaluating how deterioration of the road surface affects the efficiency of vehicles. Some research has suggested this can have a major impact (15), but would be dependent on how maintenance procedures are optimized to maintain good surface quality of roads.

Other issues were evaluated, in particular how much other material components (not just pavement) contribute to emissions. Of these additional components, drainage structures, pipes, and curbs are associated with non-trivial emissions, much of this is because these are manufactured from concrete. We also evaluated which GHG emissions are important. Not surprisingly the largest component is CO$_2$ emissions, however CH$_4$ associated with upstream emissions are important to also capture. Other species, namely N$_2$O, SF$_6$, and Black Carbon are relatively minor.

While actual vehicle traffic that uses the highway over its 50 year lifetime will create substantial GHG emissions, the construction and maintenance of the road account for almost 20% of the GHG emissions that can be attributed to the highways existence. This is higher than the average 10% reported by (25).

The decision points available to a state transportation agency in how they can minimize emissions are somewhat limited. Minimizing traffic disruption during construction is obviously one way to reduce emissions, although this was not the case for this project. Biofuels can be used in construction equipment, but this would likely add only small reductions in total emissions. As the bulk of emissions are associated with upstream processes it is not likely that a transportation agency can make decisions that lead to substantial reductions. Maintenance activities that reduce road deterioration and methods of altering albedo effects, may be opportunities for larger reductions, but research in these areas is limited (19).

This is one case study and while it is broadly representative of common road reconstruction projects, broad generalizations of these results may be limited. In particular, traffic disruption emissions are likely atypical. We have also not examined GHG emissions associated with construction of culverts and bridges.
ACKNOWLEDGMENTS

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