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Carbon Footprint Estimator, Phase II
Volume I - GASCAP Model

FINAL REPORT
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16. Abstract
The GASCAP model was developed to provide a software tool for analysis of the life-cycle GHG emissions associated with the construction and maintenance of transportation projects. This phase of development included techniques for estimating emissions from induced travel when a project involves a capacity expansion; a life-cycle maintenance module based on recommended procedures for maintaining a road surface over 50 years; an automated method for inputting construction equipment activity associated with selected project types; a method based on the Highway Capacity Manual for estimating emissions associated with project staging and the diversion of traffic around a worksite; methods for more easily updating emissions factors in the model; and, a variety of miscellaneous upgrades to account for SF_6 emissions, upstream electricity emissions associated with asphalt, and incorporation of additional bid-sheet codes in the materials module. Four case studies to demonstrate the models usage were also conducted. These were: a large project case study (reconstruction of rt 35 in Ocean County) that demonstrated the full capabilities of the model; a smaller project (rt 47 resurfacing in Gloucester County) that focused on different staging options and the impact on emissions from traffic; an applied case study conducted in collaboration with NJDOT staff in the South Jersey regional office that focused on maintenance activities; and a demonstration of the relationship between the embodied fuel cost of a project and the GHG emissions. The software and related documentation is available for use on www.gascap.org and users are requested to upload any analysis results to provide information for further development of the software.

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EXECUTIVE SUMMARY

Volume I of this report summarizes the phase II development of the GASCAP software for analyzing the life-cycle greenhouse gas (GHG) emissions of transportation capital construction projects. GASCAP is a spreadsheet-based tool that has been designed to provide estimates of GHG emissions for the many different components of a construction project. It is designed to be both user-friendly and flexible, allowing the user to specify inputs for a variety of different modules. GASCAP provides life-cycle emissions estimates for the major GHGs. These include carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), sulfur hexafluoride (SF_6), and black carbon (BC). We also include estimates for the oxidation to CO_2 of volatile organic compounds (VOC) and carbon monoxide (CO).

The primary modules within GASCAP provide estimates of embodied emissions associated with a wide range of materials, construction equipment used on a project site, emissions associated with project mobilization and traffic disruption based on how the project is staged, and life-cycle maintenance over the lifetime of the project. Other modules include procedures for using recycled materials, induced travel effects, and rail capital projects.

This phase of the GASCAP project focused on a variety of tasks. These included the development of the induced travel module, development of a life-cycle maintenance module, automated methods for allocating equipment to project types, development of procedures to estimate emissions associated with traffic disruption during project construction, various miscellaneous upgrades including development of SF_6 emissions factors, upstream asphalt emissions factors associated with electricity, and incorporation of additional bid sheet item codes. Procedures were also included in Volume II of this report which will allow NJDOT staff to update emissions factors derived from the MOVES, NONROAD, and GREET models. This phase also included the development of four case studies that provided a test of the GASCAP software and also provided useful information for decision makers.

Induced Travel Module

The induced travel module was developed to provide GHG estimates based on the traffic generated from new construction. As part of this work, we used New Jersey data to estimate models linking vehicle miles of travel to lane miles for different functional road classifications. These elasticities of travel demand, with respect to lane mileage, were then used to build the induced travel module.

Life-cycle Maintenance Module

A life-cycle maintenance module was developed that provides estimates of emissions associated with road surface maintenance over the lifetime of a project. This module is based upon a maintenance schedule provided by NJDOT engineering staff. Both asphalt and concrete pavements can be modeled. Bridge maintenance activities are not included in the module as information on typical maintenance activities was not supplied by NJDOT. The large variability in bridge types would in any case make generalizations about maintenance activities difficult for modeling purposes.

Upgrades to Equipment Module

The first phase of GASCAP required users to input the equipment types and hours of usage for each project. In this phase of the work we examined various research projects and databases to determine methods for allocating equipment and its usage to a sample of the most common project types. A study conducted in California provided the best estimates for up to seven project types and the phases of construction work associated with each. The allocation method was implemented in GASCAP allowing the user to simply specify the length of the project and what type of project it is, greatly simplifying the task of inputting this information.

Traffic Disruption and Diversion

In the first phase of GASCAP, a module was developed that provided options for staging of construction projects. This module focused on mobilization (i.e., movement of resources to the site) and options for providing project lighting powered by generators or the grid for nighttime work (a separate module developed in phase I can estimate GHG emissions from alternative street lighting options). In this phase we developed procedures that handle traffic disruption and diversion associated with the work site. The user is allowed to specify from seven different staging options, including the specification of a detour route around the work site. This allows the estimation of emissions associated with any disruption and diversion of traffic. Traffic flow equations from the Highway Capacity Manual provide the basis for determining changes in flow speeds, allowing changes in GHG emissions from a base case to be estimated.

Miscellaneous Upgrades

Various minor upgrades of the software were also completed. These include development of SF_6 emissions factors and upstream asphalt emissions factors associated with electricity usage. We also incorporated a large number of additional bid sheet items, primarily electrical components that were not included in phase I of this project.

Case Studies

As part of this project we conducted four case studies, each of varying magnitude and with different objectives. One overall objective was to test the software and provide a demonstration of its capabilities. These case studies include one large comprehensive road reconstruction project (Rt 35 in Ocean County), one focused on the traffic disruption module (Rt 47 in Gloucester County), applied work done in cooperation with the maintenance staff of the South Region NJDOT office, and a fourth which demonstrated the ability to analyze embodied fuel costs associated with projects.

During the course of this work, we found various software bugs which were fixed and various minor omissions to GASCAP, including many item codes which could not be located. These would likely have a minor impact on total emissions calculated but might be worth including in any future update. Overall the case studies demonstrated that GASCAP is generally user-friendly and will provide useful information to project managers and decision makers.

We worked closely with the South Region office to develop a special maintenance module suitable to their needs. This was a useful exercise in that it showed a practical application of the software. Staff in the South Region office input various projects and provided the output of that work. These were for specific road maintenance tasks for crack sealing, manual patching, and a pothole killer. The latter cases may not have been correctly entered, suggesting additional training work may be necessary.

Both the large case study (Rt 35) and the traffic disruption case study (Rt 47) found that the bulk of emissions are associated with materials used in the road project. Many of the smaller components used on a project, when added together, also add non-trivial emissions to a project. The finding that it is mainly embodied emissions associated with materials that accounts for most emissions, limits the ability of NJDOT to influence the GHG emissions of most projects. Equipment emissions are a minor component. Staging procedures do show some variation depending on how a project is staged; in particular, total road closures will increase emissions substantially relative to intermittent closures (as shown with the Rt 47 case study). Nighttime lighting can also contribute substantial emissions to a project, but not enough to offset the emissions from a full road closure during the day.

Our fuel cost analysis showed that total embodied fuel costs may be a good proxy for total emissions. Lower cost projects likely have fewer total emissions than higher cost projects, mainly because fewer materials are used.

Updating Procedures

The emissions factors which GASCAP uses in all phases of its calculations are derived primarily from three models. These are the EPA MOVES and NONROAD models for on-road vehicles and construction equipment, respectively, and the Argonne National Laboratory GREET models, for fuel cycle and vehicle cycle for embodied material emissions. Each of these models is periodically updated to reflect new research and changes in technology and regulations. For this reason, in Volume II of this report, we included our developed procedures and documentation that will allow NJDOT staff to update the output of these models.

Future Research

As part of this work we investigated procedures for including road deterioration and how this affects the GHG emissions of vehicles using the road. This is potentially a large source of emissions that is currently not accounted for in GASCAP. Resources were unavailable to implement a module that would account for this. This should be a priority for any future upgrades to GASCAP.

Various updates to different modules include automating the input of bid-sheet codes, more detailed research on equipment activity, possibly including a large survey of construction sites, and optimal life-cycle bridge maintenance procedures need to be developed by NJDOT and included in GASCAP.

Another issue is that GASCAP is now a fairly large and complex software product. Migration of the software to a platform more suitable to handle its complexities is recommended.

Finally, the case studies we conducted are just a start. We feel that far more work should be done to analyze various projects, both to test the software and to demonstrate its capabilities. Volume II of this report includes a GASCAP User Guide. Ideally NJDOT staff should be trained in how to use the software and policies should be put in place to integrate the use of the software within the planning process.

INTRODUCTION

New Jersey's Global Warming Response Plan (GWRP) seeks to significantly reduce carbon emissions from the transportation sector by 2050. One of the specific action items listed within the draft implementation plan is to develop methods to analyze the lifecycle carbon footprint of transportation projects. This will allow an assessment of how the actual construction and maintenance of various facilities will affect carbon or more specifically greenhouse gas (GHG) emissions. In particular, the development of a methodology for assessment can provide a useful criterion for project selection and for providing incentives and guidance to contractors and NJDOT staff to take GHG emissions into account in how they design and build capital projects.

To accomplish this goal, the Alan M. Voorhees Transportation Center at Rutgers University has developed the GASCAP (the Greenhouse Gas Assessment Spreadsheet for Transportation Capital Projects) model. This is the second phase of this research following on the initial development completed in 2011. During the first phase of development GASCAP integrated a variety of existing data sources into an easy to use system that permits an analysis of project life-cycle greenhouse gas (GHG) emissions. GASCAP includes estimates for CO_2, CH_4, and N_2O emissions, the primary greenhouse gases. It also includes estimates of Black Carbon (BC) emissions from construction equipment and HFC leakage from air conditioning units.

The GASCAP tool includes components to estimate the emissions from the primary materials used in construction projects (asphalt, concrete, and steel) as well as including a procedure to input detailed information from project bid-sheets (such as components for drainage, culverts, pipes, and other minor bid-sheet items used in projects). Equipment emissions are derived from EPA's NONROAD model and for biofuels from the GREET model developed by the Argonne National Laboratory.

GASCAP also includes a module for estimating emissions from project staging (mobilization). This provides estimates for moving materials, equipment, and labor to a jobsite, as well as lighting for night work. A module for estimating rail construction emissions is also included. In addition, as part of the original project, a comprehensive review of how transportation capacity can induce additional travel was conducted. This review suggested various approaches for modeling these effects in a sketch planning model.

This second phase of the project had several key objectives: 1) complete a module that can account for induced travel associated with capacity expansions; 2) complete a module that can account for planned maintenance schedules over the lifetime of a project; 3) add a module to account for traffic delay and diversion for a variety of project staging approaches; 4) develop a method for estimating equipment activity for some common project types; and, 5) train NJDOT staff and receive feedback on assumptions and the usability of the software. In addition, various minor upgrades and revisions to the software were completed, including the development of easier techniques for updating the emissions factors in the model. In addition, four case studies were conducted to demonstrate the use of GASCAP and to provide analytical results to understand the primary sources of emissions from project construction.

In addition we have developed a website (gascap.org). This site will provide access to the software for potential users and will include the final reports of both projects and any papers generated from this work. Software users will be encouraged to upload reports based on their use of the software and to report to us any problems or issues that they find in using the software. This will allow various upgrades to be made in the future and will provide a good beta test of the software.

This final report consists of documentation produced over the course of this work and a summary of the four case studies. It serves to complement the software product which is the primary product of this research.

DEVELOPMENT OF AN INDUCED TRAVEL PROCEDURE

The induced travel component of GASCAP accounts for vehicle miles traveled (VMT) generated by capacity additions to the road network, defined as lane mile additions. An in-depth review of the induced travel literature conducted as part of Phase I of this project showed that a consensus exists that changes in travel, measured in VMT, are affected by changes in road capacity, measured in ways that can be predicted by the laws of supply and demand.[(1)]

In order to develop New Jersey specific estimates, data on vehicle travel and changes in road capacity were needed. Several sources of data were examined as part of this project, but most proved insufficient. In the end, the only suitable data was aggregate lane mile and VMT data at the county level which was available for the years 1999-2010. Various econometric models were developed that link lane miles for different road types to VMT on those roads.

The data for the regression models include lane miles and VMT, demographic control variables, and gasoline price data for each county in the state between 1999 and 2010. Lane miles and VMT were taken from the Roadway Information and Traffic Counts web page of NJDOT.[1] Both lane miles and VMT were broken down by detailed functional classification including interstates/turnpikes, freeways/expressways, principal and minor arterials, major and minor collectors and local roads. Categories were split by urban and rural status. Demographic control variables were included for each year and county, from the US Bureau of Economic Analysis (BEA).[2] Variables that can influence VMT include population, employment, household income, earnings, inflows, and outflows. Inflows and outflows refer respectively, to earnings of local residents who are employed in other counties and earnings of outside residents who are employed in the specified county. To reduce multi-collinearity in our estimates, inflows and outflows were excluded from the final analysis and earnings was divided by employment and included as mean earnings. Household income was excluded from the analysis because income was included as part of another variable. Gasoline prices were taken by year at the state level for New Jersey from a US Energy Administration (EIA) database.[3] Gasoline prices and mean earnings were deflated to 2000 dollars using consumer price index deflators for metropolitan New York City[4] and Philadelphia[5], for the respective North and South Jersey counties in each region.

Lane mile elasticities for VMT are estimated using regression models, and show the responsiveness of VMT to changes in lane miles of road capacity. The models use natural logs of the dependent, independent, and control variables to address non-linearity. Difference models can also be estimated that express all variables as proportional growth. Dummy variables are used to capture fixed effects of time and

[1] http://www.state.nj.us/transportation/refdata/roadway/vmt.shtm
[2] http://www.bea.gov/
[3] http://www.eia.gov/state/seds/hf.jsp?incfile=sep_prices/tra/pr_tra_NJ.html&mstate=New%20Jersey
[4] http://www.bls.gov/ro2/nycpi9120.pdf
[5] http://www.psba.org/issues-advocacy/issues-research/funding-finance/cpi-u.asp

location in a cross-sectional time-series regression, also known as a fixed effects model. Models were estimated for freeways, arterials, collectors, and local roads.

After mean earnings and gasoline prices were converted to real dollars, natural logs were computed for all functional classifications of lane miles and VMT, all demographic control variables, and real gasoline prices. The data were estimated with a fixed effect regression with year specified as the time variable and FIPS county code specified as the cross-sectional variable. Variance Inflation Factor (VIF) tests were run on the results to examine multi-collinearity among the control variables. Inflows, outflows and household income were eliminated. The difference of the natural logs of earnings and employment was calculated to get the natural log of mean earnings. Fixed effects panel regression was performed on difference models for each of the four functional classifications using Stata, a general-purpose statistical software package. Hausman tests were used to compare the fixed effects and random effects models and were not significant, confirming our expectation that the data should be estimated using fixed effects models.

Modeling Results and Implementation in GASCAP

Table 1 shows the elasticities produced as a result of this analysis. Lane mile elasticities for all functional classifications of roads are not inconsistent with short term elasticities found in the literature reviewed in phase I [(1)]. The lane mile coefficient is positive and statistically significant at above the 95% level of confidence, agreeing with our hypothesis that increased lane miles are associated with increased VMT. The coefficients are equivalent to elasticities and as can be seen higher functional classifications of roads have a larger elasticity value; that is, increased capacity on interstates/freeways have the largest inducing effect, while increased local road capacity has the smallest. This result is consistent with our expectations that higher functional classifications of roads will have the largest impact on travel behavior.

Population and mean earnings are not statistically significant in any of the models, perhaps due to relatively little change over time. Gasoline prices are statistically significant at the 95% confidence level for arterial and local roads with a negative effect, but not for interstates/freeways and collector roads.

In order to link lane mile increases to GHG emissions, emissions factors were extracted from the MOVES model for 2012 as the base year. These included emissions factors for CO_2, CH_4, N_2O, and black carbon. These were aggregated to the four categories of functional classification. The emission factors were then converted to a VMT basis by dividing by VMT.

To operationalize this in GASCAP, users will be asked to enter the number of lane miles added or removed and the functional classification of the road. GASCAP will then multiply the functional classification specific lane mile elasticity by the functional classification specific emissions factors. The change in VMT is the product of the number of lane miles added and the elasticity for the applicable functional classification of the road. The change in GHG emissions due to induced travel is the product of the change in VMT and MOVES emissions factors. Table 2 displays the information in the GASCAP model.

Table 1 - Induced travel regression models - Lane mile elasticities

Freeways/Expressways/Interstates					**Arterials**				
	Coef.	SE	t	sig.		Coef.	SE	t	sig.
Lane Miles	1.007	0.058	17.42	<.001	Lane Miles	0.538	0.066	8.11	<.001
Population	-0.944	1.354	-0.70	0.487	Population	-0.027	0.713	-0.04	0.970
Mean Earnings	-0.154	0.274	-0.56	0.574	Mean Earnings	0.046	0.145	0.32	0.752
Gasoline Price	2.960	2.587	1.14	0.254	Gasoline Price	-3.158	1.349	-2.34	0.020
Rho	0.051				Rho	0.038			
F (13,176)	32.05				F (13,176)	7.46			
sig. (F)	<.001				sig. (F)	<.001			
Collectors					**Local Roads**				
	Coef.	SE	t	sig.		Coef.	SE	t	sig.
Lane Miles	0.759	0.097	7.81	<.001	Lane Miles	0.255	0.067	3.79	<.001
Population	0.925	0.954	0.97	0.334	Population	0.629	1.235	0.51	0.611
Mean Earnings	-0.088	0.192	-0.46	0.646	Mean Earnings	0.272	0.252	1.08	0.282
Gasoline Price	-0.532	1.818	-0.29	0.770	Gasoline Price	-6.262	2.335	-2.68	0.008
Rho	0.101				Rho	0.038			
F (13,176)	15.16				F (13,176)	12.29			
sig. (F)	<.001				sig. (F)	<.001			

Table 2 - Application of induced travel lane mile elasticities to GASCAP

Lane Mile Elasticities (E_i)

Expressways Freeways Interstates		
E_1 =	1.006931	VMT per new lane mile added or lost
Arterial Roads		
E_2 =	0.537502	VMT per new lane mile added or lost
Collector Roads		
E_3 =	0.758727	VMT per new lane mile added or lost
Local Roads		
$E_{4=ni}$ =	0.254975	VMT per new lane mile added or lost

Change in VMT = Elasticity x Change in LM

Expressways Freeways Interstates		
LM x E_1 =	3.021E+00	Total vehicle miles traveled
Arterial Roads		
LM x E_2 =	1.613E+00	Total vehicle miles traveled
Collector Roads		
LM x E_3 =	2.276E+00	Total vehicle miles traveled
Local Roads		
LM x $E_{4=ni}$ =	7.649E-01	Total vehicle miles traveled

Functional Classification Emission Factors (EF_{jk}) from MOVES

	CO_2 (g)	CH_4 (g)	N_2O (g)	BC (g)	CO_2e (g)
	$EF_{j,1}$	$EF_{j,2}$	$EF_{j,3}$	$EF_{j,4}$	$EF_{j,5}$
Expressways Freeways Interstates					
$EF_{1,k}$ =	510.702	8.680E-03	1.593E-02	3.058E-02	510.882
Arterial Roads					
$EF_{2,k}$ =	507.822	9.652E-03	1.829E-02	1.968E-02	508.023
Collector Roads					
$EF_{3,k}$ =	495.837	9.087E-03	1.729E-02	2.154E-02	496.025
Local Roads					
$EF_{4,k}$	503.538	9.450E-03	1.793E-02	2.035E-02	503.735

Change in GHG = Change in VMT x Emission Factors

	CO_2 (g)	CH_4 (g)	N_2O (g)	BC (g)	CO_2e (g)
	$EF_{j,1}$	$EF_{j,2}$	$EF_{j,3}$	$EF_{j,4}$	$EF_{j,5}$
Expressways Freeways Interstates					
$EF_{1,k}$ =	1,542.724	2.622E-02	4.812E-02	9.237E-02	1,543.269
Arterial Roads					
$EF_{2,k}$ =	818.866	1.556E-02	2.949E-02	3.174E-02	819.189
Collector Roads					
$EF_{3,k}$ =	1,128.613	2.068E-02	3.935E-02	4.904E-02	1,129.043
Local Roads					
$EF_{4,k}$	385.169	7.229E-03	1.371E-02	1.557E-02	385.319

OPTIMAL LIFE-CYCLE MAINTENANCE FOR BRIDGES, CULVERTS, AND PAVEMENT

The Task 3 deliverable for phase I of the Carbon Footprint Project [(1)] was a review of maintenance and rehabilitation procedures for pavements and bridges. That review documented the theoretical application of life cycle-cost analysis (LCCA) to maintenance scheduling. LCCA was mandated for the design and engineering of bridges, tunnels, and pavement projects for metropolitan and state planning under the Intermodal Surface Transportation Efficiency Act (ISTEA) of 1991 and for projects worth more than $25 million under the National Highway System Designation Act of 1995. Under the Transportation Equity Act for the 21st Century (TEA-21), LCCA was made a recommended but voluntary component of decision making in transportation planning that supplements but does not replace the expert opinions of engineers.

As previously documented [(1)], LCCA is intended to maximize performance of transportation facilities by minimizing the net present value of all costs associated with pavements, bridges and other assets. Consideration is given to DOT costs including design, construction, rehabilitation and maintenance, as well as the costs to users. The residual salvage value accrues to the DOT. Previously it was concluded that estimating life-cycle cost for pavements had less uncertainty than for bridges because of the greater service life and the greater variety of designs associated with bridges in comparison with pavements. The balance of the LCCA discussion in the previous report is a catalog of maintenance and rehabilitation activities including expected service life of each activity, associated with asphalt and concrete pavements and bridges of various types. Activities associated with pavement were taken from the New York State DOT Comprehensive Pavement Design Manual.[(2)] Activities associated with bridges and culverts were taken from the On-line Bridge Maintenance Manual Preventive Maintenance/Repair Guidelines for Bridges and Culverts published on the webpage of the Ohio DOT [(3)]. Both sources provided state-relevant estimations of service life of each type of repair presented, but in neither case was it possible to estimate a default maintenance plan based on the available information.

Because the previous report did not provide useable default maintenance plans for pavements, bridges and culverts and because we anticipated the publication of a National Cooperative Highway Research Program (NCHRP) report that would address estimation of service life for highway assets, the present maintenance deliverable was included in Phase II of the Carbon Footprint Estimator project. NCHRP Report 713 Estimating Life Expectancies of Highway Assets was published in two volumes including guidance [(4)] and an extended literature review.[(5)] In addition, a number of papers were published in the last 18 months that deal with an apparent association between higher roughness, as measured by the International Roughness Index (IRI), and lower fuel efficiency for highway users. These are reviewed in this report. An Excel spreadsheet [(6)] tool that provides default maintenance plans for asphalt and concrete pavements was found on-line on the website of the Pennsylvania DOT (PennDOT) in association with the Pavement Policy Manual.[(7)] The spreadsheet implements PennDOT's policy guidelines.

Review of Life-cycle Maintenance Reports

Asset management depends on the effective operational understanding of the causes and rates of deterioration of highway assets [(4)]. Optimal maintenance requires the simultaneous minimization of deterioration and costs. This depends on an effective understanding of the mechanisms that increase deterioration rates and the extent to which maintenance and rehabilitation measures can slow or reverse deterioration. [(4)] NCHRP Report 713 recommends modeling methods so that transportation planning entities can estimate the predicted service life of their assets. Factors that impact asset survival rates include climatic factors and the following factors taken based on:[(4)]

- Traffic volume.
- Use by heavy trucks.
- Correction of safety problems.
- Improvement of maintenance and rehabilitation strategies.
- Obsolescence due to changes in development patterns.
- Wearing and fatigue damage.
- Extreme events such as crashes and flooding.
- Maintenance costs that exceed the opportunity cost of replacing the asset.

The best candidates for maintenance planning are those assets that are valuable enough to justify the expense of preventive maintenance and rehabilitation, and the maintenance or rehabilitation of which will extend the service life of the assets. For GASCAP we assume that these assets include pavements, bridges, and box culverts. For inclusion in asset management planning, preventive maintenance activities must be shown to be cost effective.[(4)] The timing of rehabilitation or replacement must also be shown to be cost effective. To do this, end states are defined for assets. Ideally statistical models are used to predict the likelihood of deterioration from one state to another [deterioration models] or failure [life expectancy models]. In the absence of local data, published data may be used to estimate life expectancy. Models include least squares regression, Markov models, Weibull survival models, Cox survival models, probit models and Monte Carlo testing. Because we do not have access to survival or deterioration data for New Jersey or a neighboring state, we are limited to using published data.

We take note that NJDOT's Culvert Management System has been documented.[8] Information from that system and other NJDOT management systems might form a basis for more data-validated assumptions for the GASCAP Maintenance Module for bridges, culverts and pavement, however this data was not made available to the project team.

The appendices of the final NCHRP – 713 report [5] include survival data in average number of years for bridge components including decks, superstructures, substructures, and channel protection measures. Survival data for box and pipe culverts are included as well. Data for survival of scour protection measures include too few observations to produce significant results.

Pavements

The PennDOT LCCA 4.4 spreadsheet [6] provides maintenance plans for asphalt and concrete pavements at five-year intervals. Fifty year service life is assumed in both cases. Asphalt overlays are assumed to have a ten-year service life with maintenance identical to asphalt pavement maintenance at five years.

Asphalt Pavement

- Longitudinal joints are cleaned and sealed and cracks are sealed at ten-year intervals.
- Shoulders are sealed at five-year intervals and repaved at 20 and 40 years.
- At ten year intervals full depth patching of deteriorated areas is followed by milling and a bituminous inlay or overlay.
- Guiderails are adjusted and drainage is corrected at 20 and 40 years.

Concrete Pavement

- Longitudinal and transverse joints are cleaned and sealed, 25% at five years and 100% at 15 and 25 years.
- At 15 years the pavement is partially diamond ground and patched.
- At 25 and 45 years, the pavement is patched receives a leveling course and bituminous overlay; transverse joints are sawed and sealed.
- Shoulders are paved with asphalt at 25 and 45 years and receive a seal coat at 30, 35, and 40 years.

- At 35 years, the asphalt overlay is patched, milled and receives an asphalt inlay; transverse joints are sawed and sealed.

- Five-year maintenance is performed on the overlay at 30 years and on the inlay at 40 years including cleaning and sealing of transverse joints and crack sealing.

- Guide rails are adjusted and drainage is corrected at 25 and 45 years.

PennDOT [6,7] specifies maintenance schedules for concrete and asphalt pavements in an Excel spreadsheet. The Pennsylvania data for pavement is considered an acceptable basis for comparison for New Jersey because the climates are similar and because the Pennsylvania Policy Manual extensively cites FHWA and AASHTO standards. This is presented in Table 3. Use of the Pennsylvania assumptions was discussed with NJDOT staff. Their conclusion was that these were not applicable to practice in New Jersey. After some discussion, NJDOT staff produced a similar schedule of life-cycle maintenance activities. These are shown in Table 4 and are the basis for the GASCAP life-cycle maintenance module.

Table 3 - PA pavement maintenance – Flexible and rigid pavement – 50 year service life

	Asphalt Pavement	**Concrete Pavement**
5 years		
	Clean and seal 25% of longitudinal joints	Clean and seal 25% of longitudinal joints
	Crack seal 500 ft. per lane mile	Clean and seal 25% of transverse joints
	Seal coat or micro surface shoulders	
10 years		
	Full depth patch 2% of pavement area	
	Mill wearing course to 2 in. depth	
	Bituminous inlay to 2 in. depth	
	Seal coat or microsurface shoulders	
15 years		
	Clean and seal 25% of longitudinal joints	Concrete patch 2% of pavement area
	Crack seal 500 ft. per lane mile	Diamond grind 50% of total area
	Seal coat or microsurface shoulders	Clean and seal 100% of longitudinal joints
		Clean and seal 100% of transverse joints
20 years		
	Full depth patch 2% of pavement area	
	Leveling course 60 lbs. per square yard	
	Bituminous overlay to 2.5 in. depth	
	Pave shoulders	
	Adjust guiderail, drainage	
25 years		
	Clean and seal 25% of longitudinal joints	Concrete patch 8% of pavement area
	Crack seal 500 ft. per lane mile	Clean and seal 100% of longitudinal joints

	Seal coat or microsurface shoulders	Clean and seal 100% of transverse joints
		Leveling course 60 lbs. per square yard
		Bituminous overlay to 4 in. depth
		Saw and seal 100% of transverse joints
		Pave shoulders
		Adjust guiderail, drainage
30 years		
	Full depth patch 2% of pavement area	Clean and seal 25% of sawed and sealed joints
	Mill wearing course to 2 in. depth	Crack seal 500 ft. per lane mile
	Bituminous inlay to 2 in. depth	Seal coat or microsurface shoulders
	Seal coat or microsurface shoulders	
35 years		
	Clean and seal 25% of longitudinal joints	Partial depth (4 in.) patch 2% of pavement area
	Crack seal 500 ft. per lane mile	Mill wearing course to 2 in. depth
	Seal coat or microsurface shoulders	Bituminous inlay to 2 in. depth
		Saw and seal 100% transverse joints
		Seal coat or microsurface shoulders
40 years		
	Full depth patch 2% of pavement area	Clean and seal 25% of sawed and sealed joints
	Leveling course 60 lbs. per square yard	Crack seal 500 ft. per lane mile
	Bituminous overlay to 2.5 in. depth	Seal coat or microsurface shoulders
	Pave shoulders	
	Adjust guiderail, drainage	
45 years		
	Clean and seal 25% of longitudinal joints	Full depth patch 2% of pavement area
	Crack seal 500 ft. per lane mile	Leveling course 60 lbs. per square yard
	Seal coat or microsurface shoulders	Bituminous overlay to 1.5 in. depth
		Saw and seal 100% transverse joints
		Pave shoulders
		Adjust guiderail, drainage

Table 4 - NJ pavement maintenance – New flexible and rigid pavement – 50 year service life

	Asphalt Pavement	Concrete Pavement
5years		
	Clean and seal 100% of open longitudinal joints	Crack seal moderate cracks
	Crack seal moderate cracks	
	microsurface or thin overlay all lanes and shoulders	
10 years		
	Clean and seal 100% of open longitudinal joints	Clean and seal 100% of longitudinal joints
	Crack seal moderate cracks	Clean and seal 100% of transverse joints
	microsurface or thin overlay all lanes and shoulders	Crack seal moderate cracks
20 years		
	Mill 2" and Overlay 2" HMA	Concrete patch 2 - 10% of pavement area*
	microsurface or thin overlay shoulders	Diamond grind 100% of total area
		Clean and seal 100% of longitudinal joints
		Clean and seal 100% of transverse joints
		Crack seal moderate cracks
30 years		
	Clean and seal 100% of open longitudinal joints	Concrete patch 2 - 10% of pavement area*
	Crack seal moderate cracks	Diamond grind 100% of total area
	microsurface or thin overlay all lanes and shoulders	Clean and seal 100% of longitudinal joints
		Clean and seal 100% of transverse joints
		Crack seal moderate cracks
40 years		
	Full depth patch 5% of pavement area	Concrete patch 2 - 10% of pavement area*
	Mill 4" and Overlay 4" HMA	Crack seal moderate cracks
	microsurface or thin overlay shoulders	Overlay with 3" min. HMA
	CIR 4" and thin overlay and	
	microsurface or thin overlay shoulders	
50 years		
	Clean and seal 100% of open longitudinal joints	Concrete patch 2 - 10% of pavement area*
	Crack seal moderate cracks	Crack seal moderate cracks
	microsurface or thin overlay all lanes and shoulders	Mill 2" and Overlay 2" HMA
Note: * - If concrete repairs exceed 10% then reconstruction and/or rubblization is considered.		

Bridges and Culverts

For bridges and culverts average survival times are available from the Appendices of the NCHRP Report 713 [5] based on Markov or Weibull analyses. For bridges and culverts, end of life criteria are taken from 0-9 ordinal ratings, the descriptions of which are specific to the type of asset or asset component. After some discussion with NJDOT staff it was decided that the variation in bridge types was too large to implement a useful procedure in GASCAP.

Bridge survival times in New Jersey are generally quite long in comparison with other states, and especially other states in the Northeast. The description for rating level 3 seems undesirable as an end state and is not discussed further. Our review of the ODOT Manual [3] suggests guidelines for these structures and suggests the following potential maintenance plan.

For decks the following measures should be taken:

- Sealing of popouts, minor scaling, and minor cracks should be undertaken every five years.

- Treatment of more severe scaling and cracks should be undertaken every 15 years.

- Full depth concrete patching should be undertaken every ten years in the latter part of a deck's service life, with at least one slab replacement, which is a 20 year repair.

- The wearing surface of pavement should be treated similar to non-bridge pavements based on material type.

For superstructure and substructure, the following measures should be taken:

- Minor repairs every five years.

- Moderate repairs every 20 years.

- One major rehabilitation.

- Channel and scour protection measures.

Survival data for channel protection measures in New Jersey are not provided [5], although there is an estimate for the Northeast. Scour protection measures are presented for New Jersey [5].

According to our review of the Ohio Manual [3], box culverts may either be made of concrete or corrugated aluminum. NCHRP – 713 [5] addresses both types of box culverts but does not publish separate average survival time estimates. While it seems likely that the survival time estimates would be different if concrete and aluminum box culverts were treated as separate populations, that option is not available. The Ohio manual [3] specifies that a replaced metal culvert has an anticipated service life of 25 years.

While GASCAP is generally capable of analyzing individual maintenance procedures as described above, it was not possible to devise a flexible and realistic life-cycle plan for bridges and culverts going into the future. NJDOT was not able to provide the research team with information on maintenance approaches used for bridges and culverts. Thus, the life-cycle maintenance module of GASCAP only includes procedures for pavement.

Road Usage, Deterioration, and GHG Emissions

Various studies [9,10,11] suggest that the relative merits of asphalt and concrete pavement and asphalt overlays, in terms of greenhouse gas (GHG) emissions reduction and energy consumption, are linked to the pavement surface. This is typically measured using the International Roughness Index (IRI) which is defined as total meters of vertical displacement per kilometer of distance traveled (m/km).[10] These studies examine how increased roughness (based on the IRI) is associated with higher fuel consumption and GHG emissions. A number of studies such as estimated the relationship between IRI and fuel consumption, but are based only on a small sample of trucks. [12]

A recent and more comprehensive NCHRP report summarizes the effect of pavement condition on vehicle operating costs.[13] This review estimated the increase of fuel consumption, tire wear, vehicle wear and maintenance costs as a function of roughness, based on field tests for fuel consumption, test track and field test data for tire wear, and a mechanistic-empirical model for wear and maintenance. The report shows decreases in fuel efficiency, especially for lighter vehicles at all levels of IRI, as IRI increases at speeds from 35-70 mph. Tire wear increases as IRI increases. Repair and maintenance costs increase for IRI levels higher than 4 m/km. Figure 1 shows correlations between fuel consumption and IRI at speeds from 25 to 70 mph for passenger cars, vans, SUVs, light trucks, and heavy trucks. The report also provides a calibration of IRI and fuel consumption for US conditions. Figure 1 is taken from Figure 3-10. Effect of Roughness on Fuel Consumption Estimated Using Calibrated HDM4 from the HCHRP report.[13]

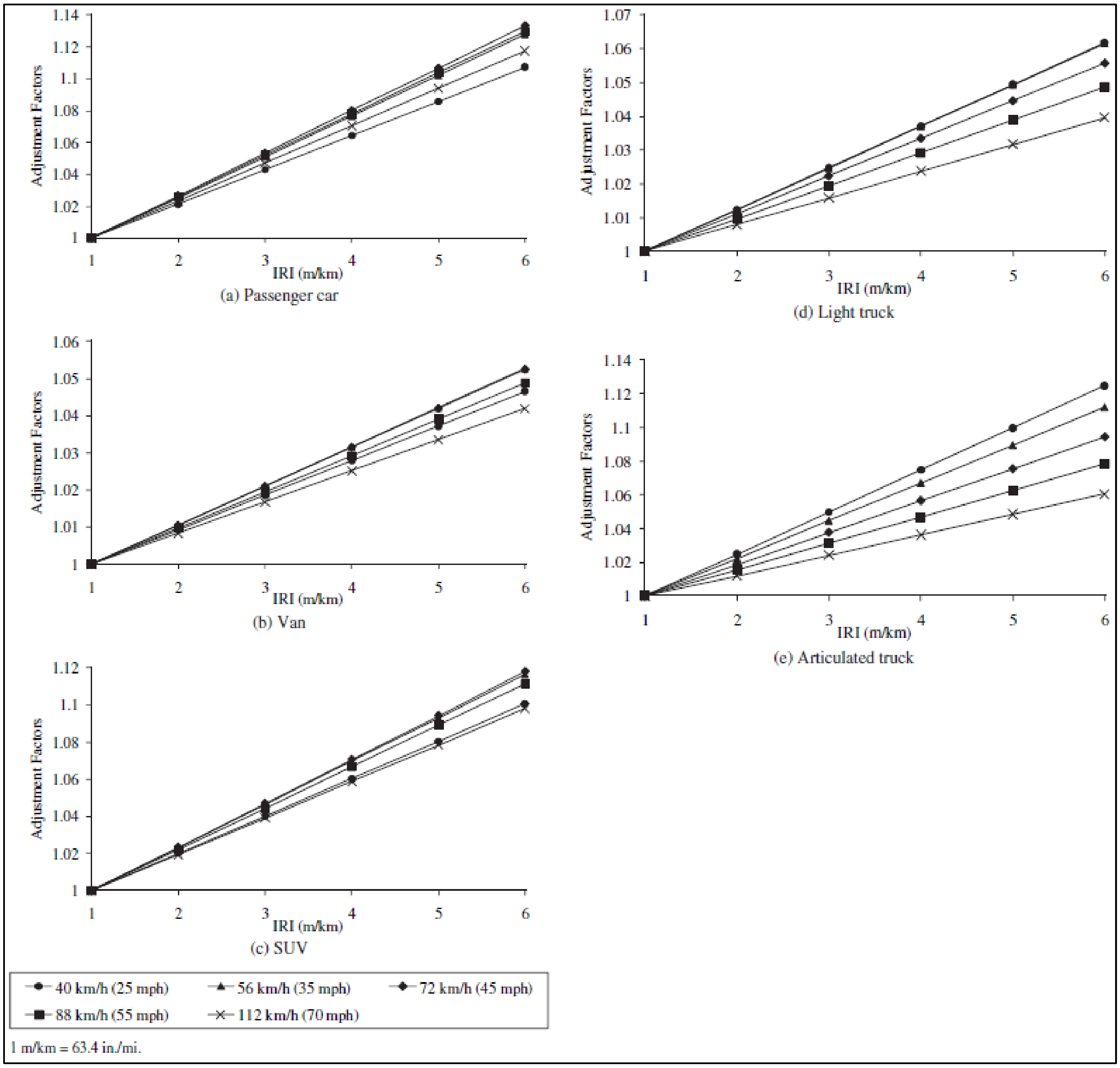

Figure 1. Effect of roughness on fuel consumption (13)

We investigated whether this data would be adequate for incorporation into GASCAP in order to account for deterioration in the road surface and how this affects GHG emissions of vehicles using the road. Ideally this could be linked to a maintenance plan that minimizes deterioration. One difficulty with implementing this approach is that NJDOT uses a combination of the IRI and a NJ standard Surface Distress Index (SDI) to measure roughness and road deterioration.[6] The World Bank provides software that can calculate IRI; we investigated implementing this in GASCAP, but were unable

[6] http://www.state.nj.us/transportation/publicat/lmreports/pdf/pavementreport2011.pdf

to do so with existing resources. This is an area that deserves more attention in any future additions to the GASCAP model.

EQUIPMENT ACTIVITY PROFILES FOR COMMON PROJECT TYPES

The initial development of GASCAP relies on the user to input information on the equipment used in a project and the hours that each piece of equipment is used. This information may not be known when a project is being analyzed. For this project the research team assessed what information is available on what equipment is used, for common project types, and the activity of that equipment.

Several approaches were examined. Our first proposed approach was to use data that NJDOT tabulates on the fuel consumption of construction projects in order to do cost adjustments to the bidded amounts in accordance with either positive or negative changes in fuel prices. During the first phase of this project, we were informed that this data was available but was being cleaned by a different university research partner team. Unfortunately, this data was never made available to our research team. A database that was provided of maintenance activities did not have the data on fuel consumption or activity of equipment.

Given the lack of New Jersey specific data, we ultimately obtained information from a study conducted in California by Kable.(15) We examined other potential sources of data, including some work being done in Arizona; this work was specific to only one specific project and the data was not readily available. Other work done in California (16) hinted that a model developed in California might be sufficient for extracting useful data. However, examination of the model determined it was not useful for our purposes. Thus, we used the California data collected by Kable,(15) and this is discussed below. The approximations are useful, but eventually NJDOT should consider collecting New Jersey specific data or make the contractor fuel consumption database available to research teams.

Equipment Activity Module

The work of Kable (15) consisted of detailed instructions for creating, and analysis of, a database of construction equipment activity used in Caltrans capital projects. Equipment definitions were taken from NONROAD. The final database included construction equipment activity data from 30 Caltrans projects that Kable categorized into seven common project types:

1. Resurface existing highway.

2. Construct freeway / extra lane.

3. Pavement rehabilitation / widening.

4. Construct / reconstruct bridge.

5. Construct median.

6. Landscaping.

7. Other, including minor bridgework.

The number of projects of each type was selected to be proportionally representative of Caltrans' general capital plan, although landscaping projects were undersampled due to lack of complete data. In addition to classifying projects by type, the database was constructed to produce equipment activity results that were disaggregated by date intervals (i.e., in which 5% increment of the project length the activity occurred) as well as by 12 project phases, selected to be consistent with the University of California Davis Construction Emissions Estimation (UCD-CT-Construct) model:

1. Land clearing and grubbing.

2. Roadway excavation.

3. Structural excavation.

4. Base and subbase.

5. Structural concrete.

6. Paving.

7. Drainage / environmental / landscaping.

8. Striping / painting.

9. Traffic Control / Signage / Barriers

10. Contract Change Orders

11. Other

12. Idle (on-site, but not operating)

Translating Caltrans Data into Default Calculations in GASCAP

The basic approach to applying the data available is to generate default equipment activity profiles both based on the duration of the project. This essentially normalizes an entire project into a single working day, the hours of which are then assigned to various equipment items. Because several pieces of equipment can sometimes be operated simultaneously, a typical equipment working day could theoretically be more than 24 hours. The estimate of total equipment hours for a project is then estimated in GASCAP by multiplying the resulting daily activity profile by the project length in days (defined by the user). Final emissions estimates would be derived by applying hourly emissions factors from NONROAD, based on the average horsepower for each type of equipment unit.

Equipment activity also varies by project phases. Data in Kable [(15)] contains the necessary information (this is also in the hidden tab in GASCAP "ActivityData"). Two separate sets of tables from Appendix A in the Kable [(15)] study are used. Table 1, for each project type, represents a profile of equipment phases (in hours), including both truck and non-road equipment. Tables 3 through 14 relate hourly truck and non-road equipment activity by project phase for each project type. Discounting the phase-level activity hours (from Table 1) by truck activity hours (since these are already accounted for in GASCAP's Staging Procedure module), then dividing the result by the average number of project days, would yield the average hours per day devoted to each phase ("Phase Hours per Day"). Tables 3 through 14 then are applied to populate an equipment-level activity profile for each phase. In this case, both the project type and proportion devoted to each of the 12 defined project phases are used as new user inputs. The workflow for a module following these guidelines is as follows:

1. Select project type.

2. Based on project type, GASCAP populates 12 fields with default values for the percentage of the project devoted to 12 defined construction phases.

3. User verifies and edits phase percentages, or accepts the default values.

4. Based on project type and length and phasing, GASCAP populates default values for hourly activity by equipment type.

5. User verifies and edits total number of hours expected for equipment types or accepts defaults.

6. GASCAP applies emissions factors based on look up tables generated from NONROAD.

This procedure adds flexibility for the user, allowing the user to tailor the proportion of each project day, devoted to the 12 defined phases of construction, to the specific project at hand. This can result in better default equipment hours. It is important to note that multiple phases can be enacted simultaneously; however, this should not present a problem, since given the number of hours devoted to each phase, each phase will form a proportion of the total time for a project, which can be idealized into a single work day of arbitrary length.

This procedure has been implemented in GASCAP and is available in the Equipment module, alongside the original equipment procedure where the user must input each piece of equipment and define how long it operates. There are three major concerns with using the Kable [15] data. First, with a total of 30 observations, the number of observations stratified by seven project types is obviously quite small. In addition, projects undertaken by New Jersey DOT or other organizations wishing to utilize GASCAP may not be comparable to Caltrans projects, for instance due to different standard construction protocols or labor markets. The second major concern is that activity must be estimated based on the duration of the project, and not the project's physical size, although the two likely correspond closely.

The third concern is methodological in nature. The data that is used provides both the initially scheduled project length in days, and the actual duration of the construction project. The latter is typically much greater than the former due to a variety of delays, such as weather. Making the data work with GASCAP hinges on the mathematical construction of a typical workday. Thus, unless any days on which no work occurred can be accounted for, the methods described above will tend to underestimate the hours per day of equipment operation. One possible solution is to simply use the number of scheduled days as the denominator for any calculation. A second solution involves investigating whether or not the "Idle" phase accounts for the hours during which equipment was not operating due to delays such as weather, and discounting the actual project duration based on idle time. A third potential solution involves assuming workdays are either 8 or 12 hour periods, and dividing this into the grand total of average equipment hours, using the resulting figure as the effective number of workdays.

The advantages of using Kable's [15] data are similarly three-fold. First, the user interface is simple and easily generates defaults with minimal parameterization, but allows a fair amount of flexibility for those more knowledgeable about construction practices. Second, the data is designed to be compatible with NONROAD; emissions factors from NONROAD are already integrated into the equipment module in GASCAP and this also makes updating easier. This also results in the ability to estimate activity and emissions for a wide variety of equipment and project types. Finally, Kable's [15] data has the advantage of being rooted in empirical observations of actual equipment activity. As previously mentioned, this is an area that NJDOT may wish to explore further to gather New Jersey specific data.

TRAFFIC FLOW, DISRUPTION, AND DIVERSION PROCEDURES

The traffic disruption module of GASCAP addresses the impacts of construction on traffic flow during the construction on a single road segment. Procedures were developed to address changes in greenhouse gas (GHG) emissions from creating work zones, closing lanes, and closing facilities and diverting traffic to alternate routes (detours). The procedures used to calculate changes in traffic flow and the consequent GHG emissions associated with those changes are documented here.

The Highway Capacity Manual (HCM) was consulted to establish flow speeds based on volume for single lane and multilane facilities [17]. Separate procedures are used to estimate flow speed for one lane and two lane collector roads. Using MOVES 2010a, GHG emissions rates per vehicle mile traveled were estimated for a range of speeds for the four functional road classifications (freeways, arterials, collectors, and local roads). GASCAP applies the HCM-derived congestion adjusted traffic flow speed and volume to the MOVES GHG emissions rates to estimate changes in vehicular emissions due to creation of a work zone, lane closure or total road closure and detour around the work zone.

Traffic Disruption Components

The GASCAP disruption module includes seven staging scenarios for traffic flow. These include:

1. <u>Work zone only</u>. In this case, there is no closure of the road, only the creation of a work zone that would slow the traffic.

2. <u>Lane closure</u>. One or more lanes are closed on a multilane facility for the duration of a construction project.

3. <u>Intermittent lane closure</u>. One or more lanes are closed for certain hours of the day while work is done in the work zone.

4. <u>Full road closure</u>. The road is closed round the clock and an alternate detour route is planned.

5. <u>Combination road and lane closures</u>. An intermittent complete road closure while work is being done in the work zone and lane closures while no work is being done in the work zone.

6. <u>Intermittent road closure</u>. Road is closed only while work is being done in the work zone.

7. Intermittent work zone. Work zone is intermittently established for certain times of the day.

In estimating GHG emissions from changes in these traffic patterns, emissions are estimated as the difference between a base scenario, assuming no construction and a proposed scenario that involves a full or partial closure of a facility, and an alternative route in the event of a full closure. Total emissions in each case are estimated with output from the MOVES model. Model inputs are taken from the HCM flow rate in passenger cars per hour per lane and the adjusted traffic volume. Various assumptions underlying the options are detailed below.

Lane Closure and Work Zone Creation

Lane closures occur only on multilane road segments. A two-lane road (one lane in each direction) is affected by establishment of a work zone, as long as there is no complete diversion of traffic. GASCAP assumes that any time a work zone is created without complete diversion of traffic, the facility capacity is reduced by 20% before calculating the impact of any lane closures.(18) Lane closures do not otherwise affect capacity in the lanes that remain open. In other words, a three lane road with one lane closed has 80% of the capacity of a two lane road with no work zone, assuming the capacity per lane was the same initially on both facilities. To close a single lane on an eight lane highway (four lanes each way) reduces capacity by a quarter in the direction of the closed lane. Closure of a single lane on a three lane highway reduces capacity by a third. If a single lane is closed on a two lane road, capacity is cut in half, but this is a special case in GASCAP because the HCM (TRB 2010) does not address a multilane highway with a single lane. This is addressed in the User Input section. It is assumed that daily volume is not changed by temporary changes in capacity and that only flow speeds are affected.

Road Closure

A road closure involves complete interruption of traffic on a single or multilane road segment in at least one direction, between a point where motorists are required to exit the facility and where they are permitted to reenter the facility. Between those two points, traffic is diverted to a segment or segments that may be of any functional classification or combination of functional classifications. For the closure scenario GASCAP assumes that all of the diverted traffic uses the detour route and that all traffic that normally uses the detour route continues to do so. Detour routes may have up to five road segments (i.e., of different functional classification). For the base case scenario GASCAP estimates emissions assuming normal flow speed and volume on the facility and for all segments of the detour route.

Intermittent and Combination Measures

Lane closures and road closures may be over any number of hours during the day and over certain days of the week. The ability to account for intermittency was incorporated into GASCAP to account for two scenarios, specifically night closures and off-peak closures. The decision was made to allow GASCAP users to specify beginning and ending daily hours for lane and road closures. As a result, hybrid strategies are possible that combine intermittent road closures and intermittent lane closures on the same projects. Work zone conditions, where they exist, are assumed to be constant. A traffic interruption strategy is considered intermittent unless it is in place 24 hours a day seven days a week. For intermittent strategies, users are asked to specify an active strategy and an inactive strategy. For example, if there is a full closure while work is underway and a lane closure at other times, the active work zone strategy is full closure and the inactive work zone strategy is closure of a certain number of lanes. In that case, users would be asked to specify the number of days in a week and the hours during the day that the work zone is active.

Inputs for GASCAP's Traffic Disruption Model

The GASCAP traffic disruption component requires users to specify a road segment and the category of traffic disruption associated with the project from the six scenarios described above. Corresponding worksheets will be displayed in GASCAP (for details, see User Guide). A preliminary screen asks users to specify the road segments to be affected by the project, including the segment in the work zone and up to five segments on any detour route. Initial data requirements include segment names or identifiers, segment lengths, whether the segments are single lane or multiple lane roads, and one of the seven staging scenarios for traffic flow listed previously. For options with intermittent closures or work zones, users will need to input the hours of the day that a road or work zone is active. A detour will also need to be specified for any complete road closure. Traffic volume data is required for the facility being reconstructed and any detour routes that are specified.

For each segment, the volume and flow speed are calculated using equations from the Highway Capacity Manual (HCM) [17] under baseline conditions before work on the project begins. Volume and flow speed are then calculated under the disrupted conditions created by the project. MOVES GHG emissions factors are applied using volume and flow speed for uninterrupted flow on the appropriate functional classification for baseline and project conditions. Traffic disruption emissions are the difference between emissions during construction or maintenance activities and the baseline emissions.

Volume and Flow Speed

Volume is assumed to vary hourly during the day. MOVES has the ability to distinguish between weekday and weekend volume, however GASCAP is not sensitive to these differences. MOVES contains default traffic volume distributions for New Jersey roads by functional classification by hour of the day, and these are used as the basis for hourly factors. These hourly factors are used instead of peak hour factors to adjust average hourly volume from Annual Average Daily Traffic (AADT) or HCM defaults. Table 5 shows the average hourly distribution of traffic volume used in GASCAP by functional road classifications derived from MOVES default values. The HCM methodologies for single and multiple lane roads are used to estimate flow speeds based on hourly volume levels.(17) For each hour, GHG emissions are estimated using MOVES, assuming volume and flow as calculated using GASCAP adaptations to the HCM method (discussed further below). The purpose of the HCM is to estimate capacity to accommodate travel demand. GASCAP uses the HCM method to estimate emissions based on predicted use. Where HCM must address maximum flow, GASCAP addresses predicted flow hour by hour over the course of a day.

Table 5 - Hourly distribution of volume by functional classification in GASCAP (19)

Time	Functional Classification			
	Freeways	Arterial Roads	Collector Roads	Local Roads
0:00-0:59	0.014	0.011	0.008	0.009
1:00-1:59	0.009	0.006	0.005	0.005
2:00-2:59	0.008	0.004	0.003	0.003
3:00-3:59	0.008	0.004	0.003	0.003
4:00-4:59	0.011	0.005	0.004	0.004
5:00-5:59	0.023	0.014	0.012	0.012
6:00-6:59	0.050	0.036	0.033	0.036
7:00-7:59	0.072	0.060	0.062	0.066
8:00-8:59	0.069	0.063	0.064	0.069
9:00-9:59	0.055	0.054	0.054	0.054
10:00-10:59	0.049	0.053	0.053	0.049
11:00-11:59	0.050	0.057	0.059	0.053
12:00-12:59	0.050	0.061	0.064	0.058
13:00-13:59	0.050	0.060	0.061	0.056
14:00-14:59	0.055	0.064	0.065	0.062
15:00-15:59	0.063	0.071	0.075	0.073
16:00-16:59	0.068	0.076	0.080	0.081
17:00-17:59	0.069	0.076	0.079	0.082
18:00-18:59	0.057	0.061	0.062	0.065
19:00-19:59	0.046	0.049	0.050	0.050
20:00-20:59	0.039	0.040	0.039	0.040
21:00-21:59	0.034	0.033	0.030	0.032
22:00-22:59	0.029	0.024	0.020	0.023
23:00-23:59	0.022	0.017	0.014	0.016
Total	1.000	1.000	1.000	1.000

Work Zone Assumptions

A work zone without a reduction in the number of open lanes reduces capacity on the facility by 20%.(18) Traffic volume is assumed to be unaffected by any slowing on the facility, because it is assumed that motorists do not consider alternate routes. The HCM is used to calculate the flow speed.

Lane Closure Assumptions

Where lanes are closed, the capacity of the facility is reduced by 20%, for the creation of a work zone. Capacity is further reduced by the proportion of lanes no longer open to traffic. The HCM is used to calculate the flow speed. It is assumed that the volume is unchanged.

Road Closure and Detours

When a road is closed it is assumed that all of the traffic uses an alternative route that consists of one or more road segments. This route is user-specified, and may consist of road segments of any functional classification. Baseline volume and flow speed are estimated independently for all segments on the detour route. When the road is closed all traffic is diverted to the detour route. This means that volume on the closed road segment is zero and each segment takes the entire volume of the closed route and its baseline volume. The increased volume is used to estimate traffic flow speed on each segment of the detour route. The HCM is used to calculate the traffic flow speed.

User Input

Users are asked to identify each road segment that is part of a work zone, a lane closure, a total closure, or detour. For each road segment, the input requirements are shown in Table 6. Defaults are shown where they exist. Table 6 lists the variables for road segments, which may be freeways, arterials, two-lane and one-lane collectors, or local roads. The values shown in Table 6 are ranges and defaults. Blank cells in the table show that a particular variable is not used for the flow and volume calculations. Check marks indicate fields that require user input because there are no defaults. These include a user-supplied segment identifier, segment length in miles, AADT, and ramp or access point density. These variables include functional classification, the number of lanes for collector and local roads, and the grade of the terrain. GASCAP provides defaults for all other variables, but these can also be overridden by the user if desired. Overrides of the HCM model default values are provided for and discussed further below.

The default values for base capacity for total flow and opposite direction flow on single lane roads, stated in passenger cars per hour are maximum values. GASCAP will process values as low as zero for these variables. The range for dominant directional flow, although not stated is from 50% to 100% of total flow. Default values for the dominant direction, opposite direction, and total flow are taken from HCM [(17)](p. 15-5). Lane closures are only possible on multiple lane roads because to close a lane on a two lane collector and arterial roads is to close the facility to traffic in the affected direction. Multiple lane collector roads are assumed to have four lanes (two in each direction). Any lane closure of a collector road can only involve a single lane. Multiple lane arterial roads may be either four or six lane roads. The range of the number of lanes that may be closed in a partial closure of freeways and arterial roads is from one lane to one less than the total number of lanes in the affected direction. Otherwise, variable defaults in ranges are stated explicitly, except for logical variables.

Table 6 - Highway Capacity Manual input variables

	Freeways	4-6 lane Arterials	4 Lane Collectors	2 Lane Col. & Art.	Local Roads	
Segment Identifier	✓	✓	✓	✓	✓	Character
Segment Length	✓	✓	✓	✓	✓	Real
Functional Class: Freeways	1					Nominal
Arterial Roads		2				Nominal
Collector Roads			3	3		Nominal
Local Roads					4	Nominal
Number Lanes (Lanes)	>=4(6) [b]	4-6(6) [b]	2	1	1	Integer
AADT	✓	✓	✓	✓	✓	Integer
Single Lane Base Capacity						
Dom. Direction Flow[d]				1,700	1,700	Integer
Total Flow[a]				3,200	3,200	Integer
Opposite Direction Flow[a]				1,500	1,500	Integer
Segment Designation: Work Zone[d]	False	False	False	False	False	Logical
Lane Closure[d]	False	False	False			Logical
Lanes Closed	Lanes – 1[a]	Lanes – 1[a]	1			Integer
Road Closure[d]	False	False	False	False	False	Logical
Detour Route[d]	False	False	False	False	False	Logical
Intermittency[d]	False	False	False	False	False	Logical
Days per week[b]	1-7(7)	1-7(7)	1-7(7)	1-7(7)	1-7(7)	Integer
Beginning Hour[d]	0:00-23:59	0:00-23:59	0:00-23:59	0:00-23:59	0:00-23:59	Time
Ending Hour[d]	0:00-23:59	0:00-23:59	0:00-23:59	0:00-23:59	0:00-23:59	Time
Lane Width[b]	>=10(12)	>=10(12)	>=10(12)	9-12(12)	9-12(12)	Integer
Posted Speed[b]		45-55(55)	35-50(40)	25-50(35)	15-30(25)	Integer
Median[d]		True	True			Logical
Ramps or Access Pts/Mile	✓ [i]	✓ [ii]	✓ [ii]	✓ [ii]	✓ [ii]	Real
Lateral Clearance: Left[b]		0-12(6)	0-12(6)			Integer
Right[b]	0-12(6)	0-12(6)	0-12(6)	0-12(6)	0-12(6)	Integer
Directional Split[b]	0.5-1.0(0.55)	0.5-1.0(0.55)	0.5-1.0(0.55)	0.5-1.0(0.6)	0.5-1.0(0.6)	Real
No Passing Lane: Level[d]				0.2	0.2%	Real
Rolling[d]				0.4	0.4%	Real
Grade[d]	Level	Level	Level	Level	Level	Nominal
Level	1	1	1	1	1	Nominal

Rolling	2	2	2	2	2	Nominal
Mountainous	3	3	3			Nominal
Urban/Rural[d]	Urban	Urban	Urban	Urban	Urban	Nominal
Prop Trucks[c]	0.05/0.12	0.05/0.12	0.05/0.12	0.05/0.12	0.05/0.12	Real
Prop RVs[c]	0.00/0.00	0.00/0.00	0.00/0.00	0.00/0.00	0.00/0.00	Real

a. Maximum
b. Range (Default)
c. Defaults Urban/Rural
d. Default

i. Ramps/mi. (segment + 3 mi upstream & 3 mi. downstream)
ii. Access points/mi. (driveways and unsignaled intersections)

When the segment worksheet is generated by GASCAP, all traffic disruption options are initialized as false. It is assumed that the option chosen is not intermittent unless the user explicitly specifies this. This means that options are implemented seven days per week, 24 hours per day for the duration of the project. If intermittency is specified as true, GASCAP generates a second worksheet for that segment to receive input for traffic disruption options when work is not actively performed in the work zone. Intermittent detour route segments are assumed to revert to their base flow and volume while the work zone is not active.

MOVES Emissions Factors

To apply the MOVES emissions factors from Table 5, GASCAP first estimates the flow speed based on volume for multiple lane roads and capacity for single lane roads using the HCM procedure. The distribution of passenger cars, trucks and buses, which are assumed to be equivalent, and recreational vehicles (RV) is taken from GASCAP's defaults or user inputs. It is assumed that passenger cars and RVs use gasoline and trucks and buses use diesel fuel for estimating emissions with MOVES. Emissions for GHGs are interpolated from MOVES per vehicle emissions factors for 5 mph speed bins or cohorts using the indicated HCM methodology. It is assumed that vehicles of all types are travelling at flow speed when applying the MOVES emissions factors. MOVES emissions factors are expressed in grams of GHG per mile.

The emissions that GASCAP reports for traffic disruption are the difference between normal volume and flow on each facility and the volume and flow while any work zone or construction activity exists on the affected road segment. As a general rule, traffic disruption decreases flow speed by reducing capacity or increasing volume. The MOVES model predicts that GHG emissions increase with decreases in flow speeds, except at freeway speeds at which they decrease with decreasing speed.

HCM Equations and Procedures

The discussion that follows outlines the HCM procedures used and any modifications made to implement these in GASCAP. At the end of each section, equations are presented for baseline or normal conditions and the disrupted conditions for each scenario type.

Multiple Lane Flow Speed and Volume

Multiple lane roads include freeways, arterial roads, and four-lane collector roads (two lanes in either direction). Flow speed is based on global assumptions for base free flow speed (BFFS) assumed to be 75.4 mph on freeways [(17)] and between 45 mph and 60 mph on other multiple lane roads.[(17)] BFSS is adjusted for lane width, lateral clearance, and access to the facility, and urban/rural variation. Posted speed limits and the presence of a median are factors that are accounted for and adjustments to flow speeds are made for multiple lane roads except for freeways. After these adjustments flow speed is adjusted for traffic volume. Annual Average Daily Traffic (AADT) is used as a basis for calculating the adjusted traffic volume. Volume is adjusted using the number of lanes, hourly fluctuations and differences in directional flow and the proportion that trucks, buses and RVs make up of traffic on the facility. HCM also allows users to correct for the proportion of unfamiliar drivers. GASCAP's default for this factor is 1, although the default can be overridden.

Free Flow Speed

Free flow speed (FFS) is the speed that a facility will support when there is no traffic, i.e. flow and density are zero [(17)](p. 10-3). FFS is the difference between a BFFS and the combined effects of narrow lanes (f_{LW}), poor side clearance (f_{LC}), and the number of ramps per mile (TRD) for freeways. The GASCAP default values for BFFS are 75.4 mph for freeways. For arterial roads and 45 mph multiple lane collector roads, the default value is the posted speed limit plus 7 mph, up to 50 mph. For all road types with a posted speed limit above 50 mph, the default value is the posted speed limit plus 5 mph. The free flow speed adjustment used for freeways is as follows: [(17)]

$$FFS = BFFS - f_{LW} - f_{LC} - (3.22 * TRD^{0.84}) \qquad (1)$$

The lane width adjustments for all multiple lane roads are 6.6 mph for lane widths between 10 and 11 feet, 1.9 mph for lane widths between 11 and 12 feet, and 0 mph for lane widths of 12 feet or greater. Table 7 shows the adjustments in miles per hour for right side clearance on freeways.

Table 7 - Freeway lateral clearance adjustment [17]

Lanes in One Direction	Freeway Lateral Clearance (Right Side)						
	>=6'	5'	4'	3'	2'	1'	0'
2	0	0.6	1.2	1.8	2.4	3	3.6
3	0	0.4	0.8	1.2	1.6	2	2.4
4	0	0.2	0.4	0.6	0.8	1	1.2
>=5	0	0.1	0.2	0.3	0.4	0.5	0.6

For multiple lane collector and arterial roads FFS is also adjusted for the effects of the lack of a median (f_M) and access point density (f_A). Access points are all driveways and intersections, which are assumed to be free flowing. The equation used for arterials is as follows: [17]

$$FFS = BFSS - f_{LW} - f_{LC} - f_M - f_A \quad (2)$$

If there is no median, f_M is set to 1.6 mph and f_A is set to 0.25 mph for every access point per mile. [17] Lateral clearance is measured on both sides of the road and differs for four and six lane highways (both sides). Refer to Table 8 for f_{LC} values.

Table 8 - Arterial and multiple lane collector road lateral clearance adjustment [17]

Lanes in One Direction	Source HCM 2010 p. 14-12 Arterial and Multiple Lane Collector Road Lateral Clearance (Both Sides)						
	>=12'	10'	8'	6'	4'	2'	0'
2	0	0.4	0.9	1.3	1.8	3.6	5.4
3	0	0.4	0.9	1.3	1.7	2.8	3.9

Traffic Volume

Annual Average Daily Traffic (AADT) is used as a basis for calculating the adjusted traffic volume. HCM's preliminary estimate of volume (V) represents the traffic flow at peak hour in the direction with the largest flow as shown in the following equation: [17]

$$V = AADT * K * D \quad (3)$$

where K is the proportion of AADT on the facility at peak hour and D is the share of flow on the facility in the dominant direction. In other words, volume is the traffic volume that flows in the dominant direction at peak hour. The default for D_d, the dominant direction, is 0.55 but users may enter any value between 0 and 1.0. [17] In the opposing direction (D_o), GASCAP calculates the balance of the flow as:

$$D_o = 1 - D_d \quad (4)$$

GASCAP substitutes K with an array of 24 hourly factors (HF_j) taken from MOVES defaults so that the volume at hour j in direction l is:

$$V_{lj} = AADT * HF_j * D_l \quad (5)$$

where D_l is the share of the flow in direction l and:

$$\Sigma HF_j = 1 \quad (6)$$

This hourly demand volume estimate is used to estimate GHG emissions. However, to account for congestion, further corrections are made. The volume is further adjusted to account for peak hour congestion, the number of lanes, the proportion of heavy vehicles, and the proportion of drivers who are not familiar with the facility. Passenger car equivalent flow rate, expressed in passenger cars per hour per lane, is estimated as follows: [(17)]

$$v_p = V / (PHF * N * f_{HV} * f_p) \quad (7)$$

where v_p is the passenger car equivalent flow rate, PHF is the peak hour congestion factor, N is the number of lanes in one direction, f_{HV} is an adjustment factor for trucks, buses, and RVs, and f_p is an adjustment factor for unfamiliar drivers. Because GASCAP uses hourly factors for all 24 hours of the day the PHF term is not used in GASCAP. GASCAP uses the following formula:

$$v_{plj} = V_{lj} / (N * f_{HV} * f_p) \quad (8)$$

where v_{pjl} is the passenger car equivalent flow rate for hour j in direction l and V_{lj} is the volume in direction l for hour j. The default for the f_p factor is 1, although it can be overridden.[(17)] The default assumption is that drivers are familiar with the facility. If the f_p term is less than 1, drivers' unfamiliarity reduces driving speeds.

The heavy vehicle adjustment factor (f_{HV}) is based on the proportion of traffic made up by trucks and buses, which are treated as comparable in their effect on passenger car volume equivalence, and RVs, which have less passenger car volume equivalence, and are often ignored. It is calculated as follows:[(17)]

$$f_{HV} = 1 / (1 + P_T(E_T-1) + P_R(E_R-1)) \quad (9)$$

where P_T is the proportion of traffic made up of trucks and buses and P_R is the proportion of traffic made up of RVs, and E_T is the passenger car volume equivalence of trucks and buses and E_R is the passenger car volume equivalence of RVs. The grade of terrain is a factor in passenger car equivalence, with larger vehicles taking up more of the road when grades are steeper. The attributes of grade specified in the HCM are level, rolling, and mountainous.[20] The following HCM defaults are used in GASCAP:

P_T 0.05 urban / 0.12 rural

P_R 0.00 urban and rural

E_T 1.5 (if level) 2.5 (if rolling) 4.5 (if mountainous)

E_R 1.2 (if level 2.0 (if rolling) 4.0 (if mountainous)

Flow Speed

The effective flow speed (FS_{lj}) in direction l for hour j is adjusted from FFS_l and v_{plj}. For freeways, the following calculations are used:[17]

$$FS_{lj} = FFS_l - A\,(\mathrm{Max}(0, v_{plj} - B))^2 \qquad \text{Freeways} \qquad (10)$$

where A is an adjustment factor and B is the break point volume taken from Table 9. The unadjusted free flow speed (FFS_l) in direction l below the break point is used to avoid reducing flow speed on an empty road.

Table 9 - Freeway flow speed curves [17]

Approximate Speed	75 mph	70 mph	65 mph	60 mph	55 mph
A	0.00001107	0.00001160	0.00001418	0.00001816	0.00002469
B	1000	1200	1400	1600	1800

For other multiple lane roads, effective flow is estimated as follows:[17]

$$FS_{lj} = FFS - A[\mathrm{Max}(0,(v_{plj} - 1400)) / B]^{1.31} \qquad \text{Non-Freeways} \qquad (11)$$

where A and B are adjustment factors taken from Table 10.

Table 10 - Non-freeway flow speed curves [17]

Approximate Speed	60 mph	55 mph	50 mph	45 mph
A	5	3.78	3.49	2.78
B	800	700	600	500

Two Lane Facilities

Single lane roads have one lane in both directions. They include some collector roads and all local roads. Single lane collector roads are classified as Class I because motorists generally expect to drive uninterrupted at higher speeds whereas local roads, which tend to have more access points and are associated with lower speeds and more stops, are classified as Class III.[17] The Class II designation refers to a specialized type of road that includes scenic routes and is not used in GASCAP. GASCAP estimates effective flow speed as average travel speed (ATS), which is appropriate for Class I and Class III roads. For the balance of this discussion, Class I roads are referred to as single lane collector roads or collectors, and Class III roads are referred to as local roads. GASCAP uses the HCM defaults for base capacity.[17] For both collectors and local roads these are:

- 1,700 passenger cars per hour in the dominant direction.
- 1,500 passenger cars per hour in the opposing direction.
- 3,200 passenger cars per hour combined base capacity.

Free Flow Speed

As with multiple lane facilities calculating FFS is the first step. For single lane roads BFFS is adjusted by a lane width and shoulder width factor (f_{LS}) and access-point density factor (f_A), i.e. intersections and driveways per mile. BFFS is set at the facility's design speed plus 10 mph. The equation is as follows:[17]

$$FFS = BFFS - f_{LS} - f_A \tag{12}$$

The factor f_{LS} is taken from Table 11. The f_A factor is the access point density multiplied by 0.25.

Table 11 - Lane width & shoulder width adjustment [17]

	Shoulder Width			
Lane Width	0-2	2-4	4-6	>=6
9-10	6.4	4.8	3.5	2.2
10-11	5.3	3.7	2.4	1.1
11-12	4.7	3.0	1.7	0.4
>=12	4.2	2.6	1.3	0.0

Traffic Volume

Hourly demand volume (V_{ij}) is calculated for the direction that is under analysis (V_{dj}) and the opposing direction (V_{oj}) and is expressed in passenger cars per hour. The GASCAP calculation is:

$$V_{lj} = AADT * ds_l * HF_j \tag{13}$$

and

$$\Sigma HF_j = 1 \tag{6}$$

where ds_l is the share of directional split that corresponds to direction l (that direction which is being analyzed). GASCAP assumes a 60/40 split as the default directional split. HF_j represents the average proportion of traffic at hour j that occurs on roads of the functional classification of the road type for New Jersey estimated from MOVES and shown in Table 5. This hourly demand volume estimate is used to estimate GHG emissions.

The demand flow rate ($v_{lj,ATS}$)is adjusted for both directions from V_{lj} based on the surge in flow at peak hour, and factors that capture the effects of grade and the proportion of heavy vehicles as follows:[17]

$$V_{l,ATS} = V_l / (PHF * f_{g,ATS} * f_{HV,ATS}) \tag{14}$$

where PHF is the peak hour factor, $f_{g,ATS}$ is the grade factor, and $f_{HV,ATS}$ is the heavy vehicle factor. The PHF is dropped in GASCAP because hourly factors are used. The equation in GASCAP is:

$$V_{lj,ATS} = V_{lj} / (f_{g,ATS\ j} * f_{HV,ATS\ j}) \tag{15}$$

The value for $f_{g,ATS\ j}$ is interpolated from Table 12. GASCAP does not allow the marginal designation for grade. In GASCAP the value for $f_{HV,ATS}$ is calculated as follows:(17)

$$f_{HV,ATS\ j} = 1 / [1 + P_T (E_{Tj} - 1)] \tag{16}$$

where P_T is the proportion of trucks and buses in traffic and E_T is the passenger car equivalence. The HCM equation includes factors for RVs, but these are not included for single lane roads in GASCAP. The value for E_T is interpolated from Table 12.

Table 12 - Grade and heavy vehicle adjustments

	Grade Adjustment			Heavy Vehicle Adj. E_T			
Directional flow 1	Level	Rolling	Marginal	Level	change	Rolling	Change
100	1.00	0.67	0.08	1.9	0.4	2.7	0.4
200	1.00	0.75	0.08	1.5	0.1	2.3	0.2
300	1.00	0.83	0.07	1.4	0.1	2.1	0.1
400	1.00	0.90	0.05	1.3	0.1	2.0	0.2
500	1.00	0.95	0.02	1.2	0.1	1.8	0.1
600	1.00	0.97	0.01	1.1	0.0	1.7	0.1
700	1.00	0.98	0.01	1.1	0.0	1.6	0.2
800	1.00	0.99	0.01	1.1	0.1	1.4	0.1
900	1.00	1.00	--	1.0	--	1.3	--
	interpolate to nearest 0.01			interpolate to nearest 0.1			

Flow Speed

The final step in estimating flow speed is to calculate average speed traveled (AST) for both directions. GASCAP uses the following formula to do this:(17)

$$AST_{lj} = FFS_l - 0.00776 * \Sigma_{lj}\, v_{lj,ATS} - f_{np,ATS\ j} \tag{17}$$

where AST_{lj} is the average speed traveled in direction l at hour j, FFS_l is the free flow speed in direction l, $v_{l,ATS}$ is the grade and heavy vehicle adjusted volume in direction l, and $f_{np,ATS}$ is an adjustment factor for the prevalence of no passing zones. The $f_{np,ATS}$ term is interpolated from Table 13, accounting for the combined effects of FFS for five speed levels, volume in the opposing direction and the proportion of the facility that does not allow passing in direction l.

Table 13 - No-passing zone adjustment [17]

Single Lane Collector and Local Roads

FFS>=65 mph					
Opposing Flow Rate pc/hour	Percent No-Passing Zones				
	<=20	40.0	60.0	80.0	100.0
<=100	1.1	2.2	2.8	3.0	3.1
200	2.2	3.3	3.9	4.0	4.2
400	1.6	2.3	2.7	2.8	2.9
600	1.4	1.5	1.7	1.9	2.0
800	0.7	1.0	1.2	1.4	1.5
1000	0.6	0.8	1.1	1.1	1.2
1200	0.6	0.8	0.9	1.0	1.1
1400	0.6	0.7	0.9	0.9	0.9
>=1600	0.6	0.7	0.7	0.7	0.8

FFS=60 mph					
Opposing Flow Rate pc/hour	Percent No-Passing Zones				
	<=20	40.0	60.0	80.0	100.0
<=100	0.7	1.7	2.5	2.8	2.9
200	1.9	2.9	3.7	4.0	4.2
400	1.4	2.0	2.5	2.7	3.9
600	1.1	1.3	1.6	1.9	2.0
800	0.6	0.9	1.1	1.3	1.4
1000	0.6	0.7	0.9	1.1	1.2
1200	0.5	0.7	0.9	0.9	1.1
1400	0.5	0.6	0.8	0.8	0.9
>=1600	0.5	0.6	0.7	0.7	0.7

FFS=55 mph					
Opposing Flow Rate pc/hour	Percent No-Passing Zones				
	<=20	40.0	60.0	80.0	100.0
<=100	0.5	1.2	2.2	2.6	2.7
200	1.5	2.4	3.5	3.9	4.1
400	1.3	1.9	2.4	2.7	2.8
600	0.9	1.1	1.6	1.8	1.9
800	0.5	0.7	1.1	1.2	1.4
1000	0.5	0.6	0.8	0.9	1.1
1200	0.5	0.6	0.7	0.9	1.0
1400	0.5	0.6	0.7	0.7	0.9
>=1600	0.5	0.6	0.6	0.6	0.7

Single Lane Collector and Local Roads					
	FFS=50 mph				
Opposing Flow Rate pc/hour	Percent No-Passing Zones				
	<=20	40.0	60.0	80.0	100.0
<=100	0.2	0.7	1.9	2.4	2.5
200	1.2	2.0	3.3	3.9	4.0
400	1.1	1.6	2.2	2.6	2.7
600	0.6	0.9	1.4	1.7	1.9
800	0.4	0.6	0.9	1.2	1.3
1000	0.4	0.4	0.7	0.9	1.1
1200	0.4	0.4	0.7	0.8	1.0
1400	0.4	0.4	0.6	0.7	0.8
>=1600	0.4	0.4	0.5	0.5	0.5

	FFS=45 mph				
Opposing Flow Rate pc/hour	Percent No-Passing Zones				
	<=20	40.0	60.0	80.0	100.0
<=100	0.1	0.4	1.7	2.2	2.4
200	0.9	1.6	3.1	3.8	4.0
400	0.9	0.5	2.0	2.5	2.7
600	0.4	0.3	1.3	1.7	1.8
800	0.3	0.3	0.8	1.1	1.2
1000	0.3	0.3	0.6	0.8	1.1
1200	0.3	0.3	0.6	0.7	1.0
1400	0.3	0.3	0.6	0.6	0.7
>=1600	0.3	0.3	0.4	0.4	0.6

Application of Emissions Factors

GHG emissions factors in grams per mile were estimated using MOVES 2010a for CO_2, CH_4, N_2O, black carbon, and CO_2e by functional classification, vehicle type, and flow speed using the MOVES speed bins. Traffic volume and flow speed for both directions over 24 hours were estimated. For this portion of the discussion, AST for single lane roads and FS for multiple lane roads are generalized as flow speed. For each of the i–species of GHG emissions were estimated using the formula below:

$$GHG_i = \Sigma_{ljk} (EF_{ijk} * V_{ljk}) * Length \tag{18}$$

Emissions factors (EF) are specific to the type (i) of GHG, time-specific flow speed at hour j, vehicle type (k), and the functional classification of the facility. Emissions factors are shown in Volume II, Appendix D. Emissions factors are expressed in grams per VMT. Volume is estimated for both directions (l), at each hour of the day (j), for each vehicle type (k). Length is the length of the facility. Data are aggregated by direction of flow, hour of the day, and vehicle type.

Vehicle types include passenger cars, trucks and buses, and recreational vehicles. Passenger cars and recreational vehicles are assumed to have gasoline engines, while trucks and buses are assumed to use diesel fuel. The default proportion of truck and bus traffic and recreational vehicle traffic are shown in Table 6 or can be provided by the user. The proportion of passenger car traffic is the residual when heavy vehicle and RV traffic are removed.

GASCAP uses this procedure to estimate GHG emissions for a baseline scenario, with no disruption of traffic, and for the work zone scenario, where traffic is disrupted. GHG emissions for traffic disruption are estimated as the difference between the disrupted scenario and the baseline scenario.

MISCELLANEOUS UPGRADES TO GASCAP

Several miscellaneous upgrades were made to GASCAP over the course of this project. These include further research into emissions factors associated with sulfur hexafluoride (SF_6) a potent GHG mainly associated with the electrical industry. As part of our research for this we also uncovered additional information to provide a full accounting of upstream electricity usage associated with asphalt production. Additional bid sheet items, not previously incorporated into GASCAP were added to the system. This focused mainly on items listed as 700 in the NJ bid sheet dataset. As discussed further below, our work on the case study revealed additional omissions of bid sheet items as the inventory of items changes over time.

Development of SF_6 Emissions Factors

An emissions factor was developed for SF_6 based on a review of existing studies and data on electricity consumption. Sulfur hexafluoride is used in circuit breakers, switch gear and other high voltage electrical equipment.

At present few papers discuss SF_6. It is recognized to have a very high global warming potential (GWP) and a long atmospheric lifetime.(21) It is not modeled in the GREET Vehicle Cycle Model.(22) The Climate Registry was used to document GWPs of GHGs covered by the Kyoto Accords, as shown in Table 14. These GWP values are based on the Intergovernmental Panel on Climate Change (IPCC) Second Assessment Report (SAR) findings published in 1996.(23) In 2007, the IPCC Fourth Assessment Report (AR4) was published (23) and reported the GWP for SF_6 is slightly less (22,800) in AR4 than in SAR (23,900) as shown in Table 14. It will be necessary to apply this difference in establishing an emissions factor for SF_6 because the source used in this memorandum reports SF_6 as CO_2e.

Table 14 - CO_2 Equivalence for GWRA defined greenhouse gases (23,24)

GHG Name	Formula	CO_2e/GWP (SAR)	CO_2e/GWP (AR4)
Carbon dioxide	CO_2	1	1
Methane	CH_4	21	25
Nitrous oxide	N_2O	310	298
Hydrofluorocarbons	Varies	12-11,700	Max. 14,800
Perfluorocarbons	Varies	6,500-7,400	Max. 13,300
Sulfur Hexafluoride	SF_6	23,900	22,800

The principal source of SF_6 appears to be leakages during manufacturing, use and dismantling of equipment; estimates of SF_6 leakage represent 78% of the total GWP of substation equipment.(26) However, given the high GWP and long atmospheric lifetime of SF_6 it is likely that substantial effort goes into minimizing leakages and recycling, resulting in a relatively minor impact overall. SF_6 is estimated to last 3,200 years in the atmosphere, which is two orders of magnitude longer than methane (12 years), and one order of magnitude longer than nitrous oxide (114 years).(25)

Table 15 shows electricity generation and SF_6 emissions from electrical transmission and distribution for materials used in GASCAP. EPA estimates SF_6 emissions in the United States from electrical transmission and distribution for 2010 at 11.8 million tonnes CO_2e.[21] US production of electricity in 2010 was 4.125 trillion kilowatt hours (kWh) [27] or roughly 2.9 grams of CO_2e per kWh, based on SAR. The GWP conversion factor (23,900) in Table 14 allows estimation of a national emissions factor for the United States of 0.1197 mg per kWh.

Table 15 - US per kilowatt hour emissions of SF_6 for 2010 from electricity transmission and distribution [21,27]

Net US Electricity Generation	4.125E+12	kWh
SF_6 emissions from Electrical Transmission and Distribution (US)	1.180E+13	grams
GWP (SAR) SF_6 emissions per kWh (US)	2.861	grams
SF_6 emissions per kWh (US)	1.197E-04	grams

Table 16 shows electricity consumption in million British thermal units (MMBtu) and kWh, applies the SF_6 emissions factor developed above and converts to CO_2e based on the AR4 standard. Electricity utilization is not included from wood and plywood, bricks, and soil since no data on these are in the GREET model and therefore estimation of SF_6 emissions for these materials was not possible. Electricity consumption from asphalt production is discussed in the next section, while other sources were derived in phase I of this project.[1]

Table 17 shows upstream SF_6 emissions from transportation fuels in brake-specific fuel consumption (BSFC), measured in pounds. Estimates of electricity in Btu were taken for the extraction and refining processes from the GREET Model for reformulated gasoline, low sulfur diesel, pure biodiesel, LPG, and CNG. LPG was assumed to be produced from 60% petroleum feedstock and 40% natural gas feedstock. Biodiesel was assumed to be from soybean feedstock. The GREET Model includes electricity consumption from soybean farming but not does not explicitly address electricity consumption in biodiesel production.[28] The SF_6 emissions factors in Table 17 are used in GASCAP and linked to the emissions derived from the NONROAD model.

Table 16- Electricity consumption and SF_6

Material	Electricity		SF_6 Emissions	CO_2e (AR4)
in tons	MMBtu	kWh	mg	grams
Asphalt Concrete	0.024	7.000	1.397	31.441
PC Concrete	0.710	209.996	40.969	934.093
Aggregate	0.013	3.830	0.754	17.202
Rolled Steel	6.019	1,764.083	347.524	7,923.556
Zinc	3.013	883.023	173.956	3,966.187
Aluminum	21.865	6,412.872	1,263.335	28,804.054
Plastic (Polypropylene)	1.211	354.909	69.917	1,594.110
Stamped Steel	6.617	1,939.370	382.056	8,710.873
Cast Iron	1.817	532.510	104.904	2,391.823
Copper	9.277	2,718.820	535.608	12,211.853
Glass	0.904	264.936	52.192	1,189.988
Lubricating Oil	Electricity is not estimated in GREET			
Fiberglass	1.823	534.269	105.251	2,399.721

Table 17 - Emissions from SF_6 associated with transportation fuels [28]

	Btu/MMBtu	kWh/MMBtu	kWh/gal.	kWh/Ft^3	kWh/kg	kWh/BSFC	SF_6 mg/BSFC
Gasoline	23,688	6.947624547	0.789264044		0.279	0.1265031	2.492E-02
Diesel	41,030	12.03398494	1.558256641		0.486	0.2204656	4.343E-02
Biodiesel *	1,011	0.296641298	0.038411488		0.012	0.0054345	1.071E-03
LPG	10,774	3.160101567	0.268450628		0.140	0.0633214	1.247E-02
CNG	29,174	8.556653096		0.008411	0.004	0.001984	3.908E-04

* The GREET Model Includes electricity from soy farming but not refining.

Upstream Electricity Emissions Associated with Asphalt Production

During phase I of the GASCAP project, one omission was that we did not have information on upstream electricity usage associated with asphalt production. This was included for Portland cement concrete. GASCAP estimates emissions from asphalt paving using a heating model so that it is sensitive to the effect of differences in heating temperatures. A heating model estimates that the energy requirement to heat one ton of HMA from 60°F to 325°F with 5% binder and 4% moisture in the aggregate is 216,461 Btu at 100% efficiency. The per ton energy consumption in the United States is estimated to be 318,649 Btu.[29] The original asphalt heating model in GASCAP addresses this gap by adjusting with an efficiency coefficient of 67.93%, which accounts for heat loss and all non-heating energy consumption. Asphalt heating is done in the United States with an 80% natural gas, and 20% residual oil mix.[30]

The previous GASCAP asphalt model differed from the concrete model in that it did not account explicitly for transportation fuels and purchased electricity in heating asphalt concrete, although electricity from refining binder and extracting aggregate were accounted for.[(28)] This section includes an estimation of electricity consumption used in asphalt production and summarizes adjustments made to the GASCAP asphalt model. The overall change in GHG emissions from asphalt production from this revision is minor.

The method for estimating an electricity consumption rate for asphalt pavement is to determine the value of electrical consumption of the asphalt paving industry as a whole using input output (I/O) tables for 2002, which is the last year that the Bureau of Economic Analysis (BEA) I/O tables are available,[(31)] find a contemporary industrial consumer price using Energy Information Administration data,[(27)] and estimate total electricity consumed by the asphalt paving industry in 2002. Asphalt sales at wholesale and retail rates are also available from the BEA I/O tables, from which an estimate of the ratio of average retail markup for asphalt paving is made. An average national bid price for asphalt pavement based on a sample of states is also used as reported by the Wisconsin Department of Transportation for 2011.[(32)] The 2011 bid price is adjusted to wholesale using the retail markup that is estimated. That price is deflated using a producer price index provided by the Bureau of Labor Statistics[(33)] for 2002 and 2011. Total production is the ratio of total sales at the wholesale rate and the wholesale price in 2002. This allows calculation of electricity consumption per ton.

Table 18 shows that in 2002, asphalt pavement producers produced roughly 289 million tons of asphalt, using 2.021 billion kWh of electricity or 7.000 kWh per ton or roughly 23,867 Btu. This is roughly 3.36% of the electricity consumption to produce an equivalent ton of concrete.

Based on 23,867 Btu of electricity consumed per ton of asphalt, the amount of heating energy modeled in GASCAP was reduced to 294,782 Btu per ton. This increases the efficiency coefficient to 73.43% from the previous estimate of 67.93%. Emissions from the electricity consumed were added back by adding an electricity consumption factor for asphalt to the emissions factors and GWP worksheet in GASCAP. The consumption factor is used not only to account for electricity consumption in asphalt production, but also to estimate SF_6 emissions. A new section was added to the asphalt model Combustion Calculator that separately estimates GHG emissions from asphalt production and adds them to the upstream emissions.

On the basis of this analysis a potentially important but in reality minor shortcoming of the phase I GASCAP model was corrected. Since electricity is a small component of the energy used in asphalt pavement production, the changes in the relative GHG reduction benefits are minor.

Table 18 - Asphalt Paving Mixture and Block Manufacturing Industry (NAICS=324121) electricity consumption per ton HMA

Electricity Consumption 2002			
Cost Purchased Electricity 2002	$95,400,000		BEA I/O Tables
Cost kWh to Industrial Customers 2002	$0.0472		EIA Website
Total kWh Consumed 2002	2,021,186,441		
HMA Sales			
Total Retail Value 2002	$9,024,600,000		BEA I/O Tables
Total Wholesale Value 2002	$7,656,500,000	84.8%	BEA I/O Tables
Average National Bid Price HMA 2011	$66.17		WSDOT Construction Cost indices
Estimated National Wholesale Price 2011	$56.14		84.8% Bid Price
Ratio Asphalt Paving PPI 2011:2002	2.117		Bureau of Labor Statistics
Estimated National Wholesale Price HMA 2002	$26.52		
Estimated HMA Consumption per Ton			
Estimated HMA Production in Tons 2002	288,730,092		
Estimated kWh Per Ton HMA	7.000		

Incorporation of Additional Bid Sheet Items into GASCAP

Phase I of GASCAP incorporated a large number of bid sheet items into the software. This allows users to input items by using bid sheet numbers specified for New Jersey. Bid sheet items in the 700 series were not included in phase I and were incorporated as part of this project. These include primarily electrical components, such as conduits, junction boxes, wires, traffic signals, cabinets and various other miscellaneous components. These and all previously entered bid sheet items are detailed in the GASCAP hidden tab “items”.

PROCEDURES FOR UPDATING EMISSIONS FACTORS IN GASCAP

The emissions factors used in GASCAP are generated primarily from four models. These are the EPA MOVES model for on-road vehicle emissions, the EPA NONROAD model for off-road construction equipment emissions, the GREET fuel-cycle model for upstream life-cycle emissions associated with fuels, and the GREET vehicle-cycle model for various upstream emissions associated with materials. Other miscellaneous emissions factors were derived from EPA’s series of AP-42 reports. All of these sources are periodically updated, in particular EPA’s emissions models provide forecasts of future year emissions. For this reason, a series of procedures for updating emissions factors have been incorporated into this version of GASCAP. Due to the complexity of the information it was not possible to completely automate these procedures and the guide to updating each is provided in Volume II, Appendices A and

B. The equipment used in the model will also require updating, as needed, and a procedure for doing this is also provided in Volume II, Appendix C.

CASE STUDIES

This section reports results from four case studies that were conducted. The objective of these case studies was to test the use of the software and provide an example of the information that can be gained from various analyses.

The GASCAP software is available at www.gascap.org. The user guide is also available at the website but is also included in Volume II, Appendix F. Additional detailed documentation, not covered here, is available in the phase I report.(1) Additional documentation is available within hidden tabs in the software. This includes "Worksheet Descriptions" which lists the purpose of each worksheet in the spreadsheet, and "Defined Names" which list the defined variables and their cell or range location in the spreadsheet. The embedded visual basic code is also accessible and provides documentation on how the software operates.

Once the website is made publically available, we will be aiming to collect case studies that users of the software will provide. This will provide a resource for future understanding of best practices for reducing emissions in construction and maintenance projects.

Overview of Case Studies

Four case studies were conducted with the objective to both test the software and to demonstrate its capabilities. Each case study focused on different aspects of the software. The first 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. The second focused on the staging and traffic disruption modules involving Route 47 in Gloucester County from Howard Street in Clayton to the vicinity of High Street in Glassboro. The third case study was based on the "special maintenance" module developed for the maintenance activities conducted by Maintenance Department personnel at the Southern Region office in Cherry Hill. The fourth case study estimated costs of fuel consumption embodied in paving materials.

First Project Case Study - Route 35 Reconstruction

This large case study was intended to demonstrate GASCAP's ability to model the GHG emissions of all aspects of a large highway reconstruction project. We evaluated the theoretical assumptions about the importance of including upstream emissions and non-CO_2 GHGs in the analysis, addressed the completeness and flexibility of the coverage of construction materials, equipment, life-cycle maintenance, staging, and traffic disruption. We also addressed the ease and convenience of data input. This case study focused on a single project: the reconstruction of a two lane state road on a barrier Island in Ocean County that was extensively damaged by Hurricane Sandy. NJDOT Contract No. 13130 is one of three federally funded projects to repair storm damage to Route 35. This project is located between Mile Posts 0 and 4 from Berkley Township to

Toms River Township, and is a two lane arterial 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 2.

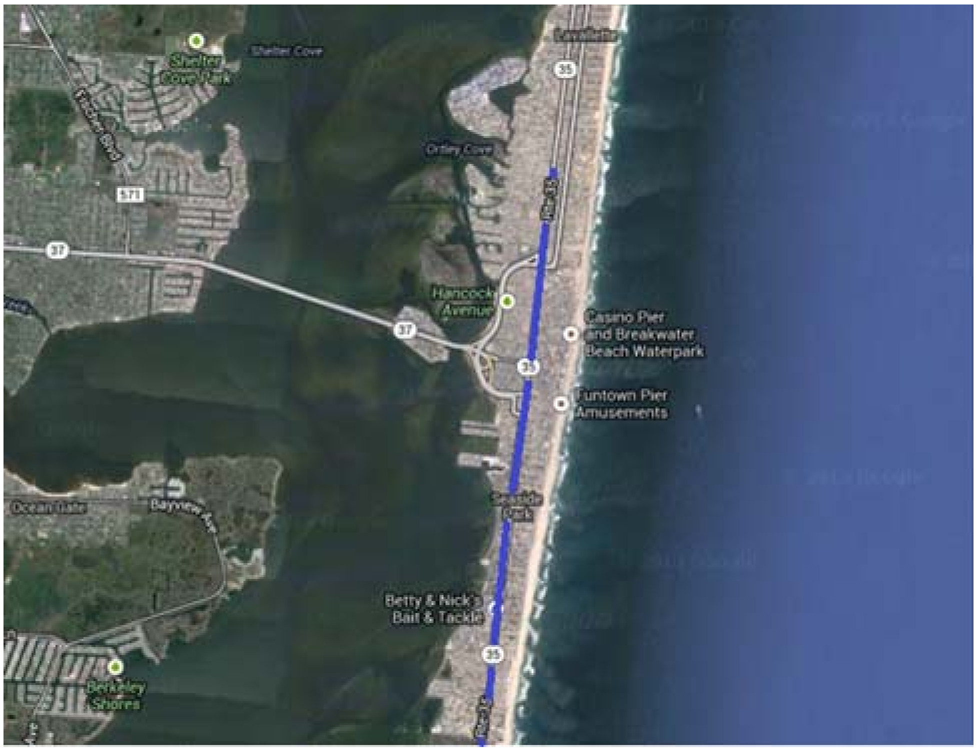

Figure 2. Approximate section of NJ Route 35 to be reconstructed under Contract 13130

Most of GASCAP's modules were used in this case study. This included the material, equipment, life-cycle maintenance, staging, and traffic disruption modules. An assessment was made of coverage of the bid sheet item codes in GASCAP, revealing that some were missing, likely due to these being continually updated. Mobilization and project lighting were handled in the staging module. An adjustment was made to the equipment modules to cover emissions from generators for project lighting. This part of Route 35 is the only arterial running through a barrier island. Because it was extensively damaged in Hurricane Sandy, it is assumed that it may be either closed or restricted along the section's length. It was assumed that the reconstructed road will have a 50 year lifetime, and the lifecycle maintenance module was used to reflect this.

The contract includes eight sections of which 97% of the budget of the successful bid is for roadway. These sections and the number of item codes included in each, as well as the value of the winning bid, are shown in Table 19.

Table 19 - Contract 13130 section attributes

Section No.	Section Title	No. of Item Codes	Cost – Winning Bid
0001	Roadway	209	$78,266,915.35
0002	Construction Engineering	5	$358,000.00
0003	Non-Participating Roadway	8	$212,585.01
0004	Erosion Control	16	$309,970.22
0005	General Landscape	11	$436,626.20
0006	Latin Landscape	11	$695,035.00
0007	Overhead Sign Support Structure No. 1	14	$233,178.70
0008	Overhead Sign Support Structure No. 2	14	$231,278.70
Total		288	$80,743,589.18

Background on GASCAP Modules

The materials module is intended to capture GHG emissions directly associated with the extraction, processing or manufacturing, and placement of specific material items. Users are asked to provide an item code, an amount based on unit type, and where called for cement and aggregate proportions for concrete, and heating temperatures, binder proportions, and the proportion of moisture in the aggregate for asphalt. Default values are provided for each of these.

Excluded from the materials module are equipment activity except asphalt heating, temporary material inputs, whether or not they are rendered not reusable by their temporary installation, and a miscellaneous category, which includes non-material and non-equipment items such as insurance, contractor's bond arrangements, price adjustments, laborers that are not associated by the item with equipment activity, such as trainees, flaggers, and similar. The remainder consists of material inputs which either are or are not included in the materials module. Material items not included in GASCAP represent gaps in the module. This analysis includes an attempt to qualitatively assess whether these gaps affect overall GHG emissions.

Equipment emissions are GHG emissions associated with the extraction, refining, and consumption of fuels used in equipment activity. These are assessed through two equipment modules. The original equipment module in GASCAP required that the user enter activity for all equipment pieces used in a project. A second equipment module provides estimates for six types of highway capital projects. For each project type, emissions are estimated for 38 equipment types. Emissions are estimated based on the NONROAD model as with the original module. Project types include:

- Resurfacing an existing highway.

- Freeway construction or addition of another lane.

- Pavement rehabilitation or widening.

- Bridge construction/reconstruction.

- Median construction, based on a thrie beam barrier.

- Landscaping.

Emissions from lifetime maintenance of the road surface only (excluding other road features, such as culverts and bridges) are assessed through the maintenance module, which is based on the engineering expertise of NJ DOT's pavement maintenance management staff. The maintenance module assumes maintenance activities of a newly constructed or reconstructed facility over a 50 year lifespan of an asphalt pavement including future material and equipment inputs. The module receives the following input from the user: pavement type, length, number of lanes and lane width in feet, pavement depth in inches, combined shoulder width (both sides) in feet, shoulder depth in inches, and the spacing of transverse joints in feet (for concrete only). Because asphalt pavement is used in this project, the traverse joint variable is not used. Values are taken from the online project description on the NJDOT webpage and a Streetview image. The exceptions use GASCAP defaults for asphalt as follows: pavement depth (8 inches) and shoulder depth (2 inches). Because asphalt is generally not expressed volumetrically there is significant uncertainty about pavement and shoulder depth which may cause inaccuracy in maintenance emissions output.

The staging module captures emissions from mobilization and project lighting. The mobilization component consists of vehicle types modeled in MOVES. These include running emissions for combination long haul and short haul trucks, light commercial trucks, passenger cars, passenger trucks, refuse trucks, which are similar to dump trucks, single unit long haul and short haul trucks, and transit buses. A wide range of vehicle types modeled in MOVES was included in GASCAP to maximize user options. Other inputs for mobilization include vintage year, fuel type, one way distance in miles, the number of one way trips, and the number of vehicles used. Project lighting allows the user to choose between generator produced electricity and electricity from the grid. In the former case, the user must first add generators in the first equipment module (a message will indicate this, if not already entered).

As the creation of any work zone or detour around a worksite will result in disruption to traffic, GASCAP estimates the emissions from the traffic that uses the road. Emissions are estimated by comparing a disrupted scenario with a base case scenario with no traffic disruption. Users are asked to select among the following measures for how traffic is disrupted or diverted around a worksite:

1. Work Zone – Establishment of a work zone with traffic control measures only in both directions.

2. Lane Closure – Closure of one or more lanes in both directions or partial closure.

3. Intermittent Lane Closure – Lane closure during some hours of the day and/or days of the week with full reopening at all other times.

4. Full Road Closure – Complete closure of the facility with an explicit detour route.

5. Intermittent Full Road Closure, Intermittent Lane Closure – Full closure some hours of the day and/or days of the week with partial closure at all other times.

6. Intermittent Road Closure - Full closure some hours of the day and/or days of the week with reopening at all other times.

7. Intermittent Work Zone - Establishment of a work zone some hours of the day and/or days of the week with reopening at all other times.

Calculations are based on the Highway Capacity Manual and thus require a number of detailed inputs to describe the road. This includes base capacity for single lane roads, intermittency characteristics for appropriate measures, and physical characteristics. Descriptive information includes a measure identifier, road length, functional classification including freeways, arterial roads, collector roads, and local roads, the number of lanes, and AADT. If the facility is a single lane road the user is asked to input base capacity for the dominant direction and total capacity for both directions. If the measure is intermittent, the user is asked to confirm that an intermittent measure is really intended and then the number of days during the week and daily start and end times for the most restrictive measure under consideration. Physical characteristics requested by GASCAP include lane width in feet, the posted speed limit, average number of ramps or access points per mile in one direction, shoulder width on each side, directional split, grade as level or rolling, the proportion of the road, if there is no median, whether there is a no passing zone, and whether the area is urban or rural. Once this information is input, the user is asked to apportion vehicle split among passenger cars, trucks and buses, and recreational vehicles (RV). Two GASCAP scenarios were considered, one which modeled a work zone only and another which modeled a single lane closure along the length of the project.

First Case Study Results

<u>Materials</u>

A review of the contract shows that of 288 bid sheet item codes, 40% of the items (115) are included in GASCAP and 25% (73) are material items not included in GASCAP.

Equipment activity accounts for 18% of contract bid items (53).The balance are temporary items (23 or 8%) or items that are not within GASCAP's scope (25 or 9%). Temporary items include construction layouts, monuments, pavement markings, drums, cofferdams, barricades, crash cushions, and fencing. While some of these items have significant mass they are largely reusable. Other temporary items, such as layouts and pavement markings have little or no material footprint. Items beyond the scope of GASCAP include personnel, paperwork, price adjustments, and temporary facilities such as field offices, laboratories, and testing equipment and activities. Pumping stations, if permanent have a considerable material footprint and represent a gap in GASCAP. A full accounting of the contract bid sheet items as classified here is shown in the appendix.

Coverage of Bid Sheet Items

Although the proportion is not quantifiable, it seems clear that a substantial majority of GHG emissions from the material footprint of this reconstruction project are covered by GASCAP. From the roadway sections (0001 and 0003) GASCAP covers all types of asphalt concrete and binder applications, all Portland cement concrete applications including concrete pipes. Most iron and PVC pipes, are also covered, as are most inlet, manhole types and signs. Among electricity-related item codes many foundation types, structures, cables and wires are covered.

Omissions from the roadway sections in GASCAP include one type of piles, three types of iron pipe, and six types of drainage structures. Considerable work went into estimating the emissions from piles, pipe, and manholes. Tide control check valves were not addressed. All 10 of these omissions represent large material footprints, and therefore noteworthy gaps. Traffic stripes and reflectors and other surface treatments are missing from GASCAP but have small material footprints. More significant omissions include fire hydrants, water valves and boxes, one type of sewer pipe, and sewer mains. Significant omissions of electrical item codes include some foundation types, structures, and conduits, although many of these items have been entered over the course of this project. A single item, a custom sign, was omitted from the non-participating roadway section (0003). No construction engineering section (0002) item codes are included.

GASCAP did not estimate any GHG emissions for the erosion control section (0004), the general landscape section (0005), or the Latin landscape section (0006). The general landscape section includes topsoil, sod, fertilization, seeding, and mulching. The Latin landscape section includes specific plantings in the landscaped area. These components are not modeled in GASCAP, although they could be addressed by revisiting the biofuels section of the GREET model. Addressing carbon offset for the specific plant species would be a complicating factor. The GHG impact of landscape materials footprint of these two sections is probably minimal.

Most of the items in the erosion control section are minor. They include fencing, haybales and similar items. Many types of fencing are handled in GASCAP. Other items may represent noteworthy gaps such as a construction driveway (asphalt) or concrete washout systems. The impact of other items is not known, for example turbidity barriers, dewatering basins, and oil remediation devices.

This Route 35 project has two sections that address overhead sign support structures (0007 and 0008). The material footprint of these structures includes reinforcement steel (rebar) and concrete for footings and electrical foundations, structures, meter cabinets, wire, and conduits. All but the conduits are included in GASCAP. Sign lighting, which is paid in a lump sum, is also not included. The meter cabinets as modeled in GASCAP do not include the meters themselves, but only the cabinets. In short, most of the material footprint of these sections is addressed in GASCAP.

Overall the data entry process for the materials module was time consuming due to the large number of item codes that had to be entered. Many of the bid sheet item codes are not found in GASCAP's materials module because the item codes represent equipment activity, temporary items, or items beyond the project's scope (about 60% of the total). When GASCAP encounters an item code that it does not recognize, it gives an error message. Future updates to GASCAP may want to consider methods for automating the input of item codes to shorten the data input time devoted to this task.

Material Emissions

Table 20 provides a breakdown of GHG emissions in megatonnes (MT) by material type, assuming hot mix asphalt heated to 325° F. Figure 3 displays a pie chart of these components. This shows that asphalt accounts for a majority (57%) of CO_2e emissions and that 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 CO_2e emissions. Many mixed materials include large amounts of reinforced concrete. Structural steel accounts for roughly 7% of CO_2e, excluding the portion used in mixed materials. The other material type emissions are minor.

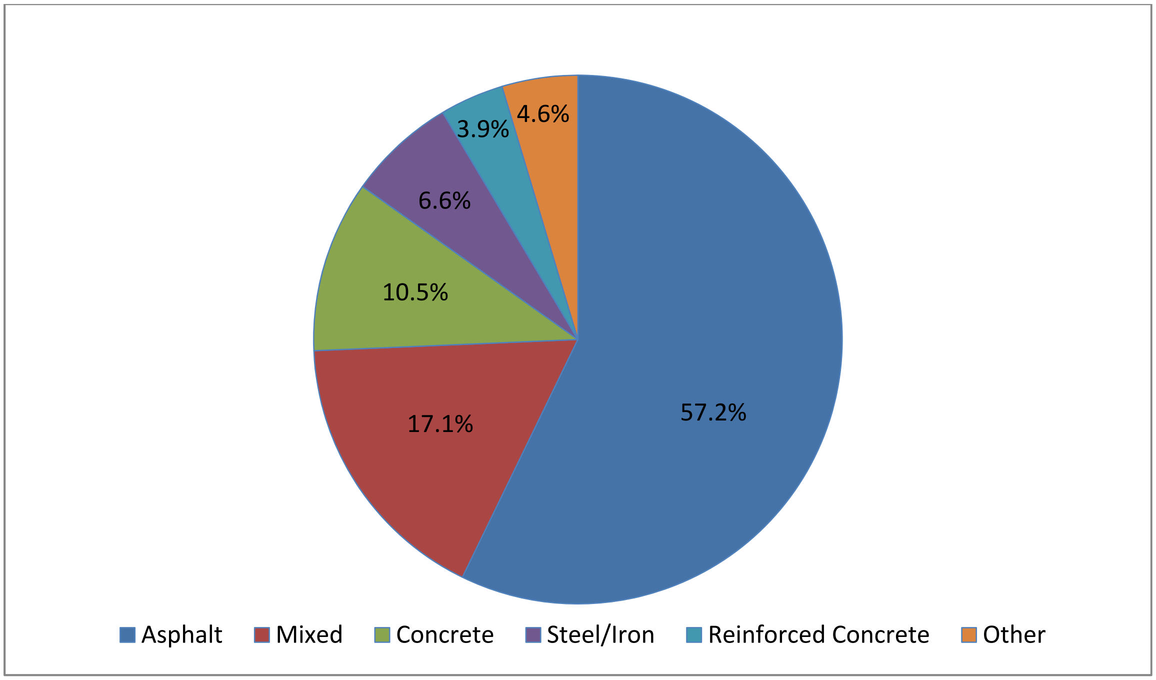

Figure 3. Material Emissions (CO_2e) for different components (NJDOT bid sheet 13130)

Table 20 - Material emissions for different components (NJDOT bid sheet 13130)

		Emissions in MT CO_2e					
By Material	Count	Upstream CO_2e		Direct CO_2e		Total CO_2e	
Aggregate	4	326.076	1.22%	0.000	0.00%	326.076	1.22%
Aluminum	3	271.553	1.02%	0.000	0.00%	271.553	1.02%
Asphalt	12	10,752.926	40.36%	4,487.105	16.84%	15,240.031	57.21%
Binder	3	259.391	0.97%	312.243	1.17%	571.634	2.15%
Concrete	14	2,798.891	10.51%	0.000	0.00%	2,798.891	10.51%
Metal	8	28.930	0.11%	0.000	0.00%	28.930	0.11%
Mixed	18	4,560.780	17.12%	0.000	0.00%	4,560.780	17.12%
Other	5	33.576	0.13%	0.000	0.00%	33.576	0.13%
Reinforced Concrete	10	1,042.528	3.91%	0.000	0.00%	1,042.528	3.91%
Steel/Iron	28	1,764.175	6.62%	0.000	0.00%	1,764.175	6.62%
Wire	10	1.546	0.01%	0.000	0.00%	1.546	0.01%
Total	115	21,840.373	81.98%	4,799.348	18.02%	26,639.721	100.00%

Substantial effort was made to make the materials module of GASCAP as complete as possible. Table 21 provides an appraisal of the fraction of each item code section and the contribution of the materials to CO_2e emissions, and this is displayed graphically in Figure 4. These are shown in descending order of importance. Nine codes associated with HMA account for most (54%) of the emissions. Considerable effort went into modeling the next three components, drainage structures, pipe, and curb, which together include 32 items and account for roughly 31% of emissions. Aggregate base courses, sidewalks, driveways, and islands, and non-vegetative surfaces account for another 10% of GHG emissions from eight items. These were relatively easy to include in GASCAP because of our work with asphalt and concrete. Utility items, including water and sewer, account for about 2% of GHG emissions in 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.

Table 21 - Material emissions for each section of bid sheet items (NJDOT bid sheet 13130)

		Emissions in MT CO_2e					
By Item Code Section	Count	Upstream CO_2e		Direct CO_2e		Total CO_2e	
Hot Mix Asphalt (HMA) Courses (401)	9	9,498.652	35.66%	4,764.346	17.88%	14,262.998	53.54%
Drainage Structures (602)	15	4,418.473	16.59%	0.000	0.00%	4,418.473	16.59%
Pipe (601)	16	2,072.673	7.78%	0.000	0.00%	2,072.673	7.78%
Curb (607)	1	1,784.432	6.70%	0.000	0.00%	1,784.432	6.70%
Aggregate Base Course (302)	3	1,701.053	6.39%	0.000	0.00%	1,701.053	6.39%
Sidewalks, Driveways, and Islands (606)	5	796.172	2.99%	3.703	0.01%	799.876	3.00%
Traffic Signals (702)	11	382.523	1.44%	0.000	0.00%	382.523	1.44%
Water Utility (651)	6	318.099	1.19%	0.000	0.00%	318.099	1.19%
Beam Guide Rail (609)	6	229.296	0.86%	0.000	0.00%	229.296	0.86%
Concrete (903)	1	186.513	0.70%	0.000	0.00%	186.513	0.70%
Sanitary Sewers (652)	4	170.116	0.64%	0.000	0.00%	170.116	0.64%
Non-Vegetative Surfaces (608)	1	50.473	0.19%	25.445	0.10%	75.918	0.28%
Other	37	231.898	0.87%	5.854	0.02%	237.752	0.89%
Total	115	21,840.373	81.98%	4,799.348	18.02%	26,639.721	100.00%

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. Since this project is not a bridge reconstruction, it is not surprising that structural concrete is a minor component. Electrical items other than those used in traffic signals are a minor component. The largest GHG emissions come from electrical foundations and structural metal. We met with limited success addressing these, however, we had better success modeling traffic signals. Sign support structures, which required substantial effort to add to the model, account for very low levels of emissions.

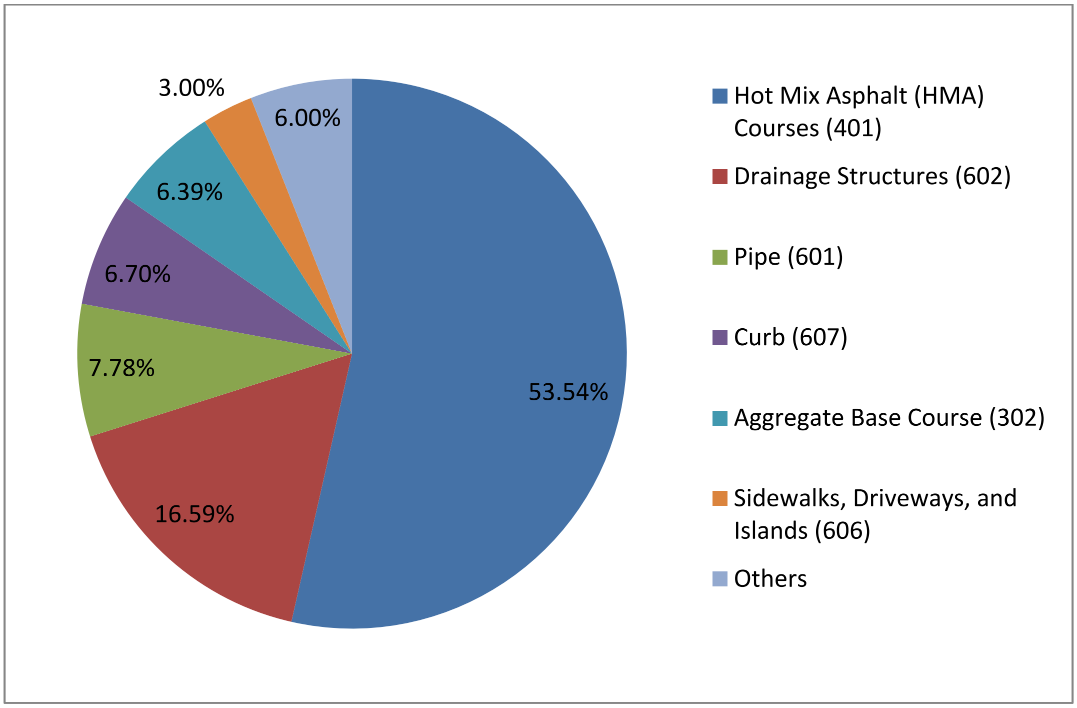

Figure 4. Material emissions for each section of bid sheet items (NJDOT bid sheet 13130)

Materials Emissions by Greenhouse Gas

A number of transportation construction models that address global warming are based only on CO_2 emissions. Arguments to justify this are based on claims that virtually all GHG emissions are from CO_2 because of its sheer volume. From the outset GASCAP was designed to model CO_2, CH_4 and N_2O, as well as the oxidation of CO to CO_2. This phase of the project also provided an opportunity to include SF_6 emissions from electricity. Table 22 breaks down materials by GHG species in CO_2e units from GASCAP output, assuming hot mix asphalt. This is done to assess the portion of non-CO_2 GHG emissions for the materials module as a whole. It was expected that non-CO_2 GHG emissions would account for a substantial and therefore non-negligible minority of GHG emissions. SF_6 emissions were incorporated into GASCAP because of the high global warming potential of SF_6. The model also includes HFC emissions from air conditioning, although this is only relevant for equipment emissions.

Table 22 shows that CO_2 emissions account for nearly all (99.5%) of direct materials emissions but significantly less (86.2%) upstream emissions. If GHG emissions accounting was based only on direct emissions, the argument to limit to CO_2 emissions would have considerable merit. However, less than one fifth (18%) of total emissions from materials are direct emissions. These are mostly from asphalt placement. Total emissions are mostly carbon, but limiting GHG emissions to CO_2 results in an undercount of total GHG emissions by about 13%. SF_6 in this case is not a major contributor to total GHG emissions.

Table 22 - GASCAP materials emissions from Project 13130 by GHG species

	Direct MT	Upstream MT	Total MT
CO_2	4,774.764	18,831.259	23,606.023
CH_4	0.176	83.792	83.968
N_2O	0.068	2.911	2.979
SF_6	0.000	0.002	0.002

	Direct MT CO_2e		Upstream MT CO_2e		Total MT CO_2e	
CO_2	4,774.764	99.5%	18,831.259	86.2%	23,606.023	88.6%
CH_4	4.397	0.1%	2,094.796	9.6%	2,099.193	7.9%
N_2O	20.187	0.4%	867.498	4.0%	887.685	3.3%
SF_6	0.000	0.0%	46.819	0.2%	46.819	0.2%
Total	4,799.348	100.0%	21,840.373	100.0%	26,639.721	100.0%

Equipment

In the second equipment module, users are asked to provide the duration in work days, as well as a single project type, and any adjustments to the activity levels for each equipment type as a percentage. The module alerts the user when percentage totals do not approximate 100%. As originally designed the second equipment module only allowed the user to select one type of project. The Route 35 reconstruction includes roadway (participating and non-participating), landscaping, and sign installation. As a result, GASCAP was edited to accommodate multiple activities. No equipment activity is associated with construction engineering, erosion control, and Latin landscape.

This project includes multiple equipment components. The roadway section was modeled as Freeway construction or addition of another lane. Equipment activity items from the contract bid sheet for the roadway section was associated with site clearing, mobilization, traffic control excavation, asphalt laying, pile driving, drainage structures, median installation, sign installation, water and sewer, traffic stripes and similar, and traffic signal installation. It was assumed that the total number of workdays was 420. The landscaping section was modeled with Landscaping as the activity type. Equipment activity items from the contract for the landscaping section include trimming and removing trees, preparing soil, and planting. It was assumed that this section would require 50 workdays. The sign installation sections included activity bid sheet items for site clearing and excavation. Because of the limited number of activity type choices in the second activity module, median installation was chosen as the best match. It was assumed that a total of 20 workdays would be required for this task. **Table 23** details the assumptions underlying the proportion of work for each phase of the project. These are linked to specific equipment types as detailed in Volume II, Appendix C, Table 22 and to specific equipment activity inputs as detailed in Volume II, Appendix C, Tables 29-32. In addition, two model year 2009 300 hp diesel generators were selected to provide a combined 600 hours of electricity for project lighting, using the first equipment module.

Table 23. Route 35 Reconstruction Equipment Activity Assumptions

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

Section 0006 Landscaping Activity	Proportion of work	Average hours/day
1 - Land Clearing and Grubbing	1.2%	0.0
2 - Roadway Excavation	0.1%	0.0
3 - Structural Excavation	0.0%	0.0
4 - Base and Subbase	2.0%	0.1
5 - Structural Concrete	0.0%	0.0
6 – Paving	0.0%	0.0
7 - Drainage / Environmental / Landscaping	82.0%	2.3
8 - Striping / Painting	0.0%	0.0
9 - Traffic Control / Signage / Barriers	0.4%	0.0
10 - Change Contract Orders	4.1%	0.1
11 – Other	10.2%	0.3

TOTAL	100.0%	2.8

Sections 0007 and 0008 Sign (Median) Installation Activity	Proportion of work	Average hours/day
1 - Land Clearing and Grubbing	0.0%	0.0
2 - Roadway Excavation	12.6%	5.1
3 - Structural Excavation	0.0%	0.0
4 - Base and Subbase	5.3%	2.1
5 - Structural Concrete	0.0%	0.0
6 – Paving	6.2%	2.5
7 - Drainage / Environmental / Landscaping	0.1%	0.0
8 - Striping / Painting	0.6%	0.2
9 - Traffic Control / Signage / Barriers	67.9%	27.3
10 - Change Contract Orders	2.2%	0.9
11 – Other	4.9%	2.0
TOTAL	99.8%	40.1

Project Lighting Activity	HP	Total hours
Generator	300	600

The equipment input assumptions are reasonable except for two issues. The first is the assumption that a sign structure installation is similar enough to median installation for the purpose of modeling. The second issue is the uninformed guesswork that established the number of days for each task, and the number of generator hours needed for the project. All of these issues could be addressed by a user who is familiar enough with transportation construction to estimate project days by task and project needs for lighting in generator hours.

The data entry process was simple and straightforward. Three project types were selected and entered from the second equipment module. The detailed equipment specifications are shown in Volume II, Appendix C. The processing time for each of the three project types was rather long. Changing the defaults is done with change buttons to the left of each record in the output, which are added when preliminary results are displayed. Given the lengthy processing time of this module, we did not examine the impact of alternative fuel types, such as B20. The first equipment module conveniently added the generators for project lighting when that was prompted by the lighting component of the staging module.

GASCAP also provides an estimate of total fuel consumption for the project. These are shown in Table 24. Fuel use appears appropriate and 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. The net contribution of equipment emissions to the total project GHG emissions is small and has little effect on total emissions.

Table 24 - Fuel used by equipment

Fuel Used	Quantity (gallons)
Gasoline (10% Ethanol RFG)	20,635.25
Gasoline	313.53
Diesel	490,736.43

Equipment Emissions by Greenhouse Gas

The relative contribution of different species to GHG emissions is similar in equipment and materials.

Table 25 shows that as with materials, CO_2 accounts for more GHG emissions because of the dramatically greater volume of CO_2 emissions.

As with materials, CO_2 has 99.5% of all direct GHG emissions. CH_4 however, accounts for a full third (33.6%) of the total CO_2e of upstream fuel emissions. Upstream equipment emissions were from diesel fuel and gasoline. The effect is the result of fugitive CH_4 emissions in the refining process. Overall the relative contribution of non-CO_2 GHG species (6.9%) to total emissions is somewhat smaller than that of materials emissions (11.4%). The contribution of SF_6 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 CO_2e emissions.

Table 25 - GASCAP equipment emissions from Project 13130 by GHG species

	Direct MT	Upstream MT	Total MT
CO_2	757.421	111.551	868.972
CH_4	0.035	2.314	2.349
N_2O	0.009	0.003	0.012
SF_6	0.000	<0.001	<0.001
PMBC	0.159	0.004	0.163
	Direct MT CO_2e	Upstream MT	Total MT CO_2e

	CO_2e					
CO_2	757.421	99.5%	111.551	64.8%	868.972	93.1%
CH_4	0.868	0.1%	57.859	33.6%	58.727	6.3%
N_2O	2.808	0.4%	0.794	0.5%	3.602	0.4%
SF_6	0.000	0.0%	1.858	1.1%	1.858	0.2%
Total	761.097	100.0%	172.062	100.0%	933.159	100.0%

Life-cycle Maintenance

The life-cycle maintenance module estimates emissions from maintenance activities based on a default maintenance plan developed from the engineering expertise of NJ DOT engineers. It does not allow the user to alter the projected maintenance activities (these are detailed in the previous chapter on this module). The output is based on materials that are used and equipment activity. The maintenance module does not account for future mobilization, traffic disruption, or project lighting. The inputs, where available, are taken from the overall parameters of the contract, the contract bid sheet. The contract bid sheet identifies all paving materials as asphalt except the subbase, which is aggregate.

The length of the contract in the project description is four miles. Streetview imagery shows a two lane road (four lanes in both directions) that appear wide enough to be 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. The pavement and shoulder depths are not readily apparent from any of these sources so GASCAP defaults are assumed for both. Pavement depth is assumed to be eight inches and shoulder depth is assumed to be two inches. If the pavement had been concrete, the pavement depth would have been known from the contract bid sheet item code descriptions, which state base and surface course thicknesses explicitly. Asphalt pavement specifications do not explicitly address thickness or volume. A rough idea of total volume could be obtained from the tonnage as stated in the contract bid sheet, and a weight to volume conversion using density could be used. However, it seems unlikely that this would be practical for the end user.

The data entry process for the maintenance module was convenient and problem-free. However, where the materials and equipment modules are designed to allow users to change default values, the maintenance module allows only a limited number of variables.

Maintenance Emissions by Greenhouse Gas

Table 26 shows the relative projected contributions of life cycle maintenance activities for 50 years. The global warming impact of upstream emissions is slightly more than twice that of direct emissions. The proportional distribution of direct emissions among GHG species is roughly identical with materials and equipment. Virtually all of the direct global warming impact is attributable to CO_2. The global warming impact of CH_4 is intermediate between its impact in materials emissions and equipment emissions. The global warming impact of SF_6 is negligible. Because maintenance activities combine equipment activity and materials use, this result was to be expected.

Table 26 - GASCAP maintenance emissions from Project 13130 by GHG species

	Direct MT	Upstream MT	Total MT
CO_2	993.347	2,041.807	3,035.154
CH_4	0.051	18.199	18.250
N_2O	0.014	0.030	0.045
SF_6	0.000	<0.001	<0.001

	Direct MT CO_2e		Upstream MT CO_2e		Total MT CO_2e	
CO_2	993.347	99.5%	2,041.807	81.4%	3,035.154	86.5%
CH_4	1.275	0.1%	454.969	18.1%	456.244	13.0%
N_2O	4.205	0.4%	9.083	0.4%	13.287	0.4%
SF_6	0.000	0.0%	2.561	0.1%	2.561	0.1%
Total	998.827	100.0%	2,508.419	100.0%	3,507.246	100.0%

Staging

Table 27 shows vehicle inputs included in the staging module, based on estimates of the vehicles needed to mobilize a project. Emissions are estimated from total miles traveled based on the inventories of material and equipment inputs and emissions factors obtained from MOVES. The distance, number of one way trips, and the number of vehicles estimated to move materials, equipment and people to the site are required inputs. These are based on engineering judgment, but could be calculated in more detail based on location of processing facilities and information on the quantity of materials to be shipped.

For this case study we do not vary the distances 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.

Volumetric measures reported in bid sheets were converted to tons based on density. Where this method was not adequate the number of trips was estimated subjectively.

Table 27 - Mobilization input assumptions

Item	Year	Fuel Type	Distance (miles)	One-Way Trips	Vehicle Miles
Single Unit Short-haul Truck	2006	Diesel Fuel	20.0	13,040	260,800
Passenger Car	2010	RFG Gasoline	20.0	7,192	143,840
Combination Long-haul Truck	2004	Diesel Fuel	20.0	28,390	567,800
Single Unit Short-haul Truck	2009	Diesel Fuel	15.5	5,328	82,584
Pickup Truck	2005	RFG Gasoline	16.0	6	96
Combination Short-haul Truck	2008	Diesel Fuel	14.5	460	6,670
Dump Truck	2006	Diesel Fuel	15.0	51,306	769,590

Air conditioning was assumed for all vehicles. Air conditioning emissions factors were applied for the entire period of the project, which is probably an exaggeration because it is assumed that during the project, the vehicles are not used for any other purpose. Unlike other GHGs, GASCAP reports HFC by CO_2e rather than by mass. GASCAP also calculates but does not show the total vehicle miles traveled.

A project lighting input was also included. GASCAP requires that the user select generators or the power grid as the electricity source. For this case study, generators were selected to power the lighting. Two model year 2009 300 hp diesel generators were used for 300 hours each for a combined total of 600 hours.

Staging Emissions by Greenhouse Gas

Table 28 shows that direct emissions account for just over 80% of emissions attributable to staging activities for a single lane closure excluding project lighting. As in the other modules direct emissions are the major source of CO_2 (>99.5%). Upstream emissions by GHG species are distributed similarly to maintenance emissions. A large majority of upstream CO_2e (88%) is from CO_2. CH_4 and N_2O account for 14.3% and 0.5% of CO_2e, respectively. Direct HFC fugitive emissions account for 0.1% of CO_2e; this may even be an overestimation as we assume air conditioners are used in all vehicles. Other GHG species contribute little. CO_2 accounts for 97% of combined CO_2e and CH_4 accounts for nearly all of the balance.

Traffic Disruption

Two scenarios were evaluated, one which modeled a work zone only and another which modeled a single lane closure along the length of the project. The impact of traffic disruption in this scenario is quite minor. Table 29 displays the total GHG emissions over the 762 day projected span of the lane closure. It is estimated to be about 1.081

MT of CO_2e. Other GHG emissions are minor. As with the mobilization scenario, the global warming of direct emissions is roughly four times that of upstream emissions. The second case study examines the staging procedure in more detail. Data including mile post locations, functional class, speed limit, presence of a median, number of lanes, lane width, and shoulder width were taken from the 2011 New Jersey Straight Line Diagrams on CD ROM (2011). Although, the Straight Line Diagrams include AADT data, AADT was taken from the NJDOT website.[7]

Table 28 - GASCAP staging emissions for a single lane closure from Project 13130 by GHG species

	Direct MT	Upstream MT	Total MT
CO_2	3,065.475	622.603	3,688.077
CH_4	0.011	4.208	4.219
N_2O	0.007	0.013	0.020
SF_6	0.000	<0.001	<0.001

	Direct MT CO_2e		Upstream MT CO_2e		Total MT CO_2e	
CO_2	3,065.475	99.8%	622.603	84.8%	3,688.077	96.9%
CH_4	0.274	0.0%	105.206	14.3%	105.480	2.8%
N_2O	2.029	0.1%	3.835	0.5%	5.863	0.2%
SF_6	0.000	0.0%	2.685	0.4%	2.685	0.1%
HFC (CO_2e)	2.304	0.1%	0.000	0.0%	2.304	0.1%
Total	3,070.082	100.0%	734.327	100.0%	3804.409	100.0%

Between Mile Posts 0 and 4, Route 35 is a two lane arterial. There are four measuring points between MP 0.1 and 4.5 inclusive. These average AADT of 8,467. According to 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. 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. It is assumed that the grade is level, and the area is urban. There are no passing zones. Vehicle split was assumed to be the same as the GASCAP default. GASCAP estimated no additional GHG emissions for a non-intermittent work zone with these assumptions. For a non-intermittent closure of one lane in both directions, added GHG emissions were calculated as shown in Table 29.

[7] Roadway Information and Traffic Monitoring System Program: Interactive Traffic Count Reports http://www.state.nj.us/transportation/refdata/roadway/traffic_counts/

Table 29 - GASCAP traffic disruption emissions from Project 13130 by GHG species

	Direct MT	Upstream MT	Total MT
CO_2	0.847	0.192	1.038
CH_4	<0.001	0.001	0.001
N_2O	<0.001	<0.001	<0.001
SF_6	0	<0.001	<0.001

	Direct MT CO_2e		Upstream MT CO_2e		Total MT CO_2e	
CO_2	0.847	99.55%	0.192	83.08%	1.038	96.04%
CH_4	<0.001	0.03%	0.037	16.13%	0.037	3.47%
N_2O	0.004	0.41%	0.001	0.65%	0.005	0.46%
SF_6	0	0.00%	<0.001	0.14%	<0.001	0.03%
Total	0.850	100.00%	0.231	100.00%	1.081	100.00%

Total GHG Emissions

Table 30 shows direct, upstream and total emissions for all components of the case study project. GASCAP's Results sheet does not separate direct and upstream emissions for the project as a whole. Direct and upstream emissions were estimated from the tables shown previously. CO_2 emissions account for more than 99% of direct emissions and 85% of upstream emissions. The relative contribution of each GHG to total emissions is consistent across the modules. This is because direct emissions are generally from fuel consumption. The process fuels and transportation fuels produce similar GHG emissions when burnt. Direct emissions account for 28% of GHG emissions. The principal sources of these emissions are from heating asphalt, transportation and non-road equipment fuel consumption.

Upstream emissions account for most of the emissions associated with this section of the Route 35 reconstruction. Again CO_2 emissions account for the lion's share of GHG emissions although CH_4 and N_2O together account for 10% of total emissions. Omission of these two GHGs would create a substantial underestimation. Omission of upstream emissions from this inventory would represent a 72 % under estimation of total emissions. The impact of SF_6 emissions is negligible. The emissions from HFCs were substantial in the staging module, but negligible in the project as a whole. The output of HFCs would have been increased if more vehicles had been specified in the staging module or if air conditioning had been specified for more non-road equipment pieces.

Table 30 - GASCAP total emissions from Project 13130 by GHG species

	Direct MT	Upstream MT	Total MT
CO_2	9,591.853	21,607.412	31,199.265
CH_4	0.273	108.515	108.787
N_2O	0.098	2.957	3.055
SF_6	0.000	0.002	0.002

	Direct MT CO_2e		Upstream MT CO_2e		Total MT CO_2e	
CO_2	9,591.853	99.60%	21,607.412	85.56%	31,199.265	89.43%
CH_4	6.815	0.07%	2,712.867	10.74%	2,719.681	7.80%
N_2O	29.232	0.30%	881.210	3.49%	910.443	2.61%
SF_6	0	0.00%	53.364	0.21%	53.364	0.15%
HFC (CO_2e)	2.304	0.00%	0.000	0.00%	2.304	0.01%
Total	9,630.204	100.00%	25,254.853	100.00%	34,885.057	100.00%

Major sources of GHG emissions

Table 31 shows the relative contributions of each module to GHG emissions for this project. The recyclables, lighting, rail, and induced travel modules were not used (and are not relevant to this case study). Upstream emissions from materials production contributed the majority of GHG emissions (63%), followed by direct materials emissions (14%). Most of the remainder of GHG emissions is from lifecycle maintenance (10%) and mobilization/staging (11%). Equipment emissions account for only 3% of GHG emissions. Clearly the largest source of GHG emissions is from materials emissions. The maintenance module has two components, equipment and the other materials. Maintenance emissions are from maintenance activities projected into the future. Since GHG emissions from materials is roughly 28 times as much as from equipment use, we should expect that most maintenance emissions are from materials production and placement. The full output as shown in GASCAP is in Volume II, Appendix C, Table 23 with additional detail on the GHG components.

Case Study Conclusions

This first case study was intended to demonstrate how GASCAP handles construction materials, equipment, lifecycle maintenance, staging, including mobilization and project lighting, and traffic disruption for a large $80 million construction project. The portion of the Route 35 reconstruction modeled here is larger than any project that has been entered into GASCAP to date.

Table 31 - GHG emissions from each module

Hot Mix		Emissions in MT CO_2e Upstream		Direct		Total	
Materials		21,840.373	62.606%	4,799.348	13.757%	26,639.721	76.363%
Equipment		171.957	0.493%	761.097	2.182%	933.054	2.675%
Recyclables	Not Modeled						
Maintenance		2,508.419	7.190%	998.827	2.863%	3,507.246	10.054%
Staging		3,070.082	8.800%	734.327	2.105%	3,804.409	10.905%
Traffic Disruption		0.850	0.002%	0.231	0.001%	1.081	0.003%
Lighting	Not Modeled						
Rail	Not Modeled						
Induced Travel	Not Modeled						
Total		27,591.681	79.092%	7,293.830	20.908%	34,885.511	100.000%

Our objective was primarily to test the capabilities of the GASCAP model and this was largely found to be successful. We also evaluated which components of the project account for the bulk of the GHG emissions. Upstream emissions embedded within the materials used in the project account for the bulk of 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 our default assumptions, may even be an overestimate as the total fuel consumption calculated seems excessive. But even then, the fraction of GHG emissions from equipment is minor. Staging and traffic disruption are also minor components, while lifecycle maintenance is an important source of emissions, primarily from the materials used in maintaining the road surface. More precise estimates of project mobilization components could possibly be added, based on location of processing facilities and quantity of materials to be shipped. This would likely have no effect on the major results given that equipment emissions are minor.

Other issues were evaluated, in particular how much other material components (not just aggregate, asphalt, and concrete) contribute to emissions. Of these additional components, drainage structures, pipes, and curbs add non-significant 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_2O, SF_6, and Black Carbon are relatively minor.

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, we have not examined GHG emissions associated with construction of culverts and bridges.

In using GASCAP we determined several areas in which the model could be improved by:

- Adding missing material item codes illustrated by this case study.
- Automating the input of item bid sheet codes.
- Improving the processing efficiency of the second equipment module, as this is slow.
- Upgrading to a more flexible architecture than Microsoft Excel.
- Adding a means to adjust maintenance based on empirically derived deterioration factors.

Second Case study of Project Staging Options and Traffic Disruption - Route 47 Resurfacing

The focus of this case study is to highlight GASCAP's traffic disruption module. GASCAP was used to model NJDOT Contract No. 11110. This contract was for pavement rehabilitation for Route 47 in Gloucester County from Howard Street in Clayton to the vicinity of High Street in Glassboro, roughly between MP 59.7 and MP 62.5. The project includes milling and paving. We include inputs for materials, equipment, and lifecycle maintenance, but focus our analysis on how traffic is disrupted during construction of the project. Life-cycle maintenance was modeled assuming an asphalt inlay, which is assumed to have a 20 year service life. The successful bid for the contract was $1.3 million. The contract was let June 2, 2011 and was scheduled for completion January 4, 2012. The roadway section of the contract accounts for 97.4% of the awarded contract amount.

The contract makes an interesting case study because it represents traffic disruption on a state road where there are few comparable alternative routes. By its nature the work will result in traffic disruption. This presents an opportunity to test the HCM-based traffic disruption equations that underlie GASCAP's traffic disruption module. Two staging scenarios are tested to examine the impact of staging alternatives on GHG emissions including a full road closure with a detour, and an intermittent full road closure using the same detour route.

This contract includes five sections of which 97.4% of the budget of the successful bid is for roadway (Section 0001). Nearly all of the balance (2.5%) is for construction engineering (Section 0002) and is outside of the scope of the material covered in GASCAP. Non-participating roadway (Section 0003) consists of two items outside of GASCAP's scope. Landscaping includes topsoiling, fertilization, seeding, and mulching for a very small area (120 square yards ~33 feet by 33 feet). Erosion control (Section

0004) consists of 16 inlet filters and oil spill kits for a budgeted cost of $405. The materials and equipment components of this project are nearly exclusively from the roadway section.

In GASCAP, traffic disruption emissions are defined as the difference between vehicle emissions in a scenario where traffic is disrupted by highway construction and a base case scenario with no traffic disruption. The two options selected for this case study are as follows:

1. Full Road Closure – Complete closure of the facility with an explicit detour route.

2. Intermittent Road Closure - Full closure some hours of the day and/or days of the week with reopening at all other times.

Users are asked to input, as required, base capacity for single lane roads, intermittency characteristics for appropriate measures, and physical characteristics. Descriptive information includes a measure identifier, road length, functional classification including freeways, arterial roads, collector roads, and local roads, the number of lanes, and AADT. The closure and detour routes were mapped with Google Maps.

Figure 5 shows a map of the closure and detour routes. The portion of Route 47 to be closed is shown in blue. The detour route is shown in red. If the facility is a single lane road, the user is asked to input base capacity for the dominant direction and total capacity for both directions. If the measure to be taken is intermittent, the user is asked to confirm that an intermittent measure is intended and then the number of days during the week and daily start and end times for the most restrictive measure under consideration.

Physical characteristics required by GASCAP include lane width in feet, posted speed limit, average number of ramps or access points per mile in one direction, shoulder width on each side, directional split, grade as level or rolling, the proportion of the road, if there is no median, if there is a no passing zone, and whether the area is urban or rural. Once this information is input, the user is asked to apportion vehicle split among passenger cars, trucks and buses, and recreational vehicles (RV). GASCAP defaults were used when data was not available.

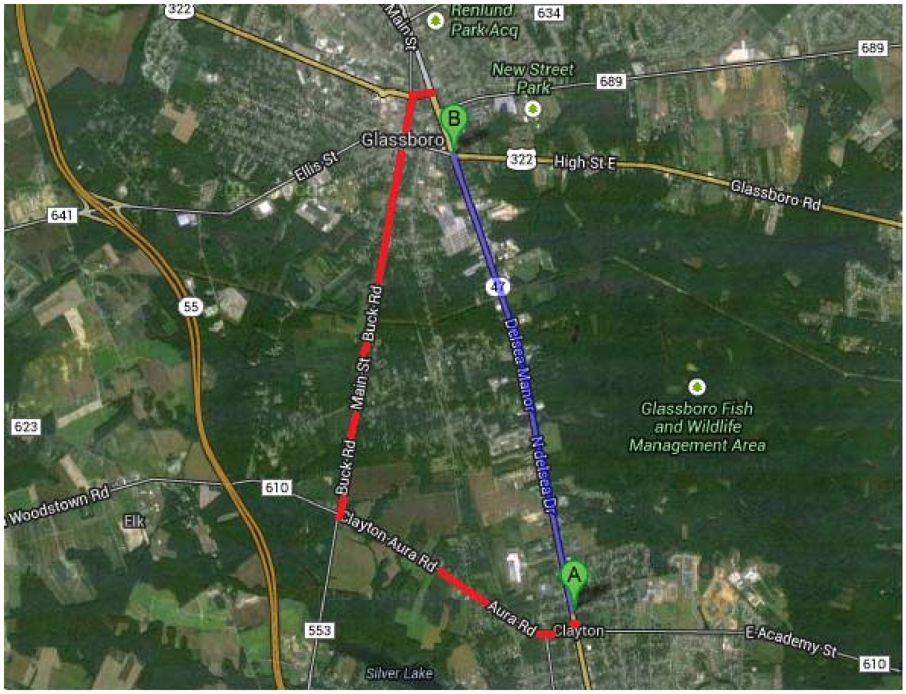

Figure 5. Approximate section of NJ Route 47 to be resurfaced under contract 11110, with detour route sections

Data including mile post locations, functional class, speed limit, presence of a median, number of lanes, lane width, and shoulder width were taken from the 2011 New Jersey Straight Line Diagrams on CD ROM (2011). Although, the Straight Line Diagrams include AADT data, AADT was taken from the NJDOT website[8] because those data are more recent. Some conversions were necessary. Lane width was calculated as pavement width divided by the number of lanes in both directions. Pavement width and number of lanes in both directions are given in the straight line diagrams. Combined shoulder width is double the single shoulder width as given in the Straight Line Diagrams. All data inputs are shown in Table 32.

This case study is based on resurfacing of a single lane arterial. It is assumed that there will be a full closure of the road and that this could be intermittent. A suitable detour route was found that includes four segments of arterial roads with similar capacity to the Route 47 segment to be resurfaced. The segment to be closed on Route 47 begins at Howard Street in Clayton (MP 59.70) and ends just south of High Street in Glassboro (MP 62.46) and has a total length of 2.76 miles. In order to avoid extreme congestion of side streets and smaller roads and in order to be able to use the New Jersey Straight Line Diagrams (2011) a diversion route was chosen that begins at CR 610, Academy Street (MP 59.51) and rejoins Route 47 at US 322, West Avenue (MP 62.87) so that through traffic is diverted from a 3.36 mile segment of Route 47.

[8] Roadway Information and Traffic Monitoring System Program: Interactive Traffic Count Reports http://www.state.nj.us/transportation/refdata/roadway/traffic_counts/

Table 32 - Closure and detour routes

Segment Name	AADT	From Mile Post	To Mile Post	Length mi	Lane width ft	Combined shoulder width ft	Speed Limit mph range	Speed Limit mph avg.
Closure								
Route 47	7,870	59.51	62.87	3.36	12	12	35 - 50	43
Detour								
US 322 - West Avenue	17,257	17.72	17.84	0.12	12	4	35	35
Co 553 - Main Street/ Buck Road	5,503	37.95	40.51	2.56	11	8	25-50	40
NJ 610 - Aura Road	3,576	0.57	1.96	1.39	12	2	35-45	41
NJ 610 - W. Academy St.	3,576	1.96	2.21	0.25	12	8	30	30
Detour Route change				0.96	11.51	6.69	25-50	37.1
Proportional change				29%	-4%	-44%		-14%

The detour route is 4.32 miles long and includes the following four segments:

- W. Academy Street – Co. 610 from MP 2.21 to 1.96 (0.25 miles)
- Aura Road – Co. 610 from MP 1.96 to 0.57 (1.39 miles)
- Main Street/Buck Road – Co. 553 from MP 37.95 to 40.51 (2.56 miles)
- West Avenue – US 322 from MP 17.72 to 17.84 (0.12 miles)

All segments including the diverted portion of Route 47 are single lane arterial roads with no median. All segments are wide enough (12 feet or more) not to incur a congestion penalty from GASCAP, which is based on HCM, except for Main Street/Buck Road which has a lane width of 11 feet for much of its length (89%). All segments of both routes have combined shoulder widths less than what is needed to avoid a congestion penalty from GASCAP and HCM (12 feet or more) except for 0.3 miles of Main Street/Buck Road on the detour route. Speed limits are quite variable on all but the shortest segments of both routes as shown in Table 32 which shows the input data. The average speed limits are weighted by distance and rounded to the nearest whole number. Changes between the base route and the detour route are weighted by VMT, except for total length. The number of access points was assumed to be 14 per mile for all segments. This assumption was based on a visual inspection of the area using Google Maps. The effect of a constant density of access points is that this correction which is modeled in HCM and GASCAP is not addressed in this case study.

The full road closure scenario assumes complete closure of the 2.76 mile length from June 2, 2011 the letting date, until January 4, 2012, the completion date of the contract (216 days). The intermittent closure scenario assumes a closure of the same segment over the same period of time limited to five days per week and only between the hours of 10:00 PM to 6:00 AM. GASCAP does not differentiate between weekdays and weekend days. The total closure increases VMT by 2,589 per day (89%). As shown in Table 32, the route length for diverted traffic is increased by 0.96 miles (29%). Average lane width is decreased slightly, but enough to incur a penalty according to HCM calculations. Speed limits are as low as 25 mph, which does not occur on the segment that is being resurfaced. The average speed limit is reduced by 6 mph (14%) on the detour route. These differences suggest that the detour route segments are all more prone to congestion than the segment to be closed.

Results show that GHG emissions from the full road closure are substantially larger than when the road is only closed intermittently (see **Table 33**). The full road closure results in nearly 700 megatonnes (MT) of GHG emissions, while the intermittent road closure contributes only 44 MT of GHG emissions. In both scenarios CO_2 accounts for the vast majority of direct GHG emissions (>=99.4%). CH_4 accounts for 16.3% of upstream GWP in both scenarios. N_2O and SF_6 make measurable but much smaller contributions to GWP.

Table 33 - GHG emissions from full closure and intermittent closure of NJ Route 47 relative to base case

Full Closure

	Direct MT	Upstream MT	Total MT
CO_2	547.317	123.340	670.657
CH_4	0.011	0.972	0.983
N_2O	0.009	0.005	0.014
SF_6	0.000	<0.001	<0.001

	Direct MT CO_2e		Upstream MT CO_2e		Total MT CO_2e	
CO_2	547.317	99.5%	123.340	82.6%	670.657	95.9%
CH_4	0.269	<0.1%	24.312	16.3%	24.581	3.5%
N_2O	2.629	0.5%	1.434	1.0%	4.063	0.6%
SF_6	0.000	0.0%	0.218	0.1%	0.218	<0.1%
Total	550.215	100.0%	149.304	100.0%	699.519	100.0%

Intermittent Closure

	Direct MT	Upstream	Total MT
CO_2	34.757	7.830	42.587
CH_4	0.001	0.062	0.062
N_2O	0.001	<0.001	0.001
SF_6	0.000	<0.001	<0.001

	Direct MT CO_2e		Upstream MT CO_2e		Total MT CO_2e	
CO_2	34.757	99.4%	7.830	82.6%	42.587	95.8%
CH_4	0.018	0.1%	1.543	16.3%	1.561	3.5%
N_2O	0.181	0.5%	0.091	1.0%	0.272	0.6%
SF_6	0.000	0.0%	0.014	0.1%	0.014	<0.1%
Total	34.956	100.0%	9.478	100.0%	44.434	100.0%

Staging

Table 34 shows mobilization inputs included in the staging module, based on rough assumptions of the typical vehicles needed to mobilize a project; we use the same assumptions for this case study. As with the first case study, emissions are estimated with total miles traveled based on the inventories of material and equipment inputs and emissions factors obtained from MOVES. The distance, number of round trips, and the number of vehicles estimated to move materials, equipment and people to the site are shown Table 34.

Table 34 - Mobilization input assumptions

Item	Year	Fuel Type	Distance (miles)	Round Trips	Vehicle Miles
Single Unit Short-haul Truck	2007	Diesel Fuel	20	104	2,080
Passenger Truck	2005	RFG Gasoline	20	12	240
Single Unit Short-haul Truck	2004	Diesel Fuel	15.5	150	2,325
Passenger Truck	2007	RFG Gasoline	16	8	128
Refuse Truck	2006	Diesel Fuel	15	1600	24,000

As with the previous case study, 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 15 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. Volumetric measures were converted to tons based on density using bid sheet data. Where this method was not adequate the number of trips was estimated subjectively.

Staging Emissions by Greenhouse Gas

Table 35 shows that direct emissions account for just over 80% of emissions attributable to staging activities for a full or intermittent road closure excluding project lighting. Direct emissions are nearly all (99%) of CO_2. A large majority of upstream CO_2e (85%) is from CO_2. CH_4 and N_2O account for 14.3% and 0.5% of CO_2e, respectively. Direct HFC fugitive emissions account for 0.1% of CO_2e. Other GHG species contribute little. CO_2 accounts for 97% of combined CO_2e and CH_4 and HFCs accounts for nearly all of the balance.

Other Sources of Emissions Associated with Construction

GHG emissions from pavement materials, equipment, and projected life-cycle maintenance are included in this case study to provide context for the relative importance of added GHG emissions from traffic disruption strategies. In all modules GASCAP estimates direct and upstream GHG for CO_2, CH_4, N_2O, and SF_6. This case study includes project lighting generator power as a factor that is included in the intermittent closure scenario but not the full closure scenario. For this reason it is estimated separately from other equipment. The details on these modules were described in the first case study.

Table 35 - GASCAP Staging Emissions for a single lane closure from Project 11110 by GHG species

	Direct MT	Upstream MT	Total MT
CO_2	47.720	9.694	57.414
CH_4	<0.001	0.065	0.066
N_2O	<0.001	<0.001	<0.001
SF_6	0.000	<0.001	<0.001

	Direct MT CO_2e		Upstream MT CO_2e		Total MT CO_2e	
CO_2	47.720	99.93%	9.694	84.91%	57.414	97.03%
CH_4	0.003	0.01%	1.637	14.34%	1.640	2.77%
N_2O	0.031	0.06%	0.052	0.46%	0.083	0.14%
SF_6	0	0.00%	0.033	0.29%	0.033	0.06%
HFC (CO_2e)	0.467	<0.97%	0	0.00%	0.467	0.79%
Total	48.221	100.0%	11.416	100.0%	59.637	100.0%

This project is an asphalt resurfacing project, assuming heating values of the asphalt are 325°F. The equipment assumptions are based on a road resurfacing with 72 work days. Equipment activity was allocated using the approach described in the equipment section of this report. In addition, because night work is assumed in the intermittent scenario two 600 hp diesel generators were modeled for eight hours per day for 72 days or a total of 1,152 hours. The life-cycle maintenance assumption for this project assumes that asphalt inlays have a projected service life of 20 years. Default assumptions in GASCAP are used except for pavement and shoulder depth (8 and 2 inches, respectively).

Table 36 shows that materials is the largest of the other components of GHG emissions (1,001 MT), followed by maintenance (793 MT). Generators for lighting account for more GHG emissions than all other equipment activity (136 MT). Non-lighting equipment emissions are relatively minor (118 MT). For direct emissions the vast majority of GHG emissions are from CO_2 emissions (>=99.5%). For upstream emissions, CO_2 emissions are largest proportionally for maintenance emissions (90.8%) for maintenance activities, followed by materials emissions (82.6%), non-lighting equipment emissions (64.9%), and generator emissions (64.2%). CH_4 emissions contribute at least 8.8% of GHG emissions across the four categories of upstream GHG emissions, but not more than 1.1% for SF_6 or N_2O.

Table 36 - GHG emissions from materials, equipment, and life-cycle maintenance from NJ Route 47 resurfacing

	Materials MT	Equipment MT	Project Lighting MT	Life-cycle Maintenance MT
Direct CO_2	344.382	96.053	110.580	141.199
Direct CH_4	0.009	0.003	<0.001	0.005
Direct N_2O	0.004	0.001	0.002	0.002
Upstream CO_2	541.100	14.224	16.016	591.145
Upstream CH_4	4.525	0.298	0.344	2.287
Upstream N_2O	0.009	<0.001	<0.001	0.037
Upstream SF_6	0.000	<0.001	<0.001	<0.001

	Materials MT CO_2e		Equipment MT CO_2e		Project Lighting MT CO_2e		Life-cycle Maintenance MT CO_2e	
Direct CO_2	344.382	99.6%	96.053	99.5%	110.580	99.6%	141.199	99.5%
Direct CH_4	0.229	0.1%	0.082	0.1%	0.014	<0.1%	0.129	0.1%
Direct N_2O	1.054	0.3%	0.355	0.4%	0.458	0.4%	0.597	0.4%
Upstream CO_2	541.100	82.6%	14.224	64.9%	16.016	64.2%	591.145	90.8%
Upstream CH_4	113.124	17.3%	7.441	34.0%	8.610	34.5%	57.171	8.8%
Upstream N_2O	0.217	0.0%	0.008	0.0%	0.068	0.3%	0.928	0.1%
Upstream SF_6	0.674	0.1%	0.238	1.1%	0.270	1.1%	1.973	0.3%

	Materials MT CO_2e		Equipment MT CO_2e		Project Lighting MT CO_2e		Life-cycle Maintenance MT CO_2e	
Total Direct Emissions	345.665	34.5%	96.490	81.5%	111.053	81.8%	141.925	17.9%
Total Upstream Emissions	655.116	65.5%	21.911	18.5%	24.964	18.2%	651.218	82.1%
Total Combined Emissions	1,000.781	100%	118.402	100%	136.017	100%	793.144	100%

Total Project Emissions

Restricting the full road closure and detour to the hours of 10:00 PM to 6:00 AM five days a week, it is possible to reduce emissions from traffic disruption by the equivalent of 519 metric tons of CO_2 compared to closing the road completely. Since the work under the intermittent scenario is done at night, generator emissions account for a relatively large share of emissions, 136 metric tons of CO_2. **Table 37** shows both the fraction of emissions from traffic disruption and the relative impact of this savings in the context of the resurfacing project as a whole. The intermittent closure reduces project

GHG emissions by about 20% in comparison with the full closure over the same time period. Of note also is that with a full road closure, traffic disruption accounts for over a quarter of total GHG emissions associated with the project. This compares to the much smaller fraction of traffic disruption in the Route 35 case study which consisted of greater quantities of materials and did not involve a road closure with a detour of traffic.

Table 37 - Total project GHG emissions NJ Route 47 resurfacing

	Full Closure		Intermittent Closure	
	MT CO_2e		MT CO_2e	
Traffic Disruption	699.519	26.18%	44.434	2.06%
Materials	1,000.780	37.46%	1,000.780	46.50%
Maintenance	793.144	29.69%	793.144	36.85%
Generators	0	0.00%	136.017	6.32%
Equipment	118.402	4.43%	118.402	5.50%
Staging/Mobilization	59.637	2.23%	59.637	2.77%
Total (less savings)	2,671.483		2,152.415	
Reduction	519.068	19.80%		

Case Study Conclusions

The traffic disruption module of GASCAP is based on HCM. The second case study presented here is based on a single case where a single lane arterial road is closed for resurfacing and an alternate route is established. All four facilities that make up the detour route are also single lane arterial roads. The GHG emissions reduction that results from limiting the full closure to eight night time hours per day five days per week is roughly 20% of total GHG emissions compared to a full closure. This case study demonstrates the uniqueness of individual projects and in this case shows the importance of traffic disruption compared to the Route 35 case study.

Special Maintenance Module and Third Applied Case Study

The life-cycle maintenance module is based on a projection of maintenance and rehabilitation activities needed over the 50 year projected lifetime of asphalt or concrete pavement, or the shorter projected service life of asphalt overlayed pavement. This module is based on the engineering expertise of pavement design engineers at NJDOT and was discussed in detail in a previous section. The module would be improved by data for routine maintenance activities, such as pothole filling and crack sealing. To our knowledge, NJDOT’s Maintenance Department does not systematically collect these data, or it is not in a format that can be readily shared with researchers.

On March 12, 2013 a meeting was held at the NJDOT headquarters in Trenton to present the GASCAP Model to selected personnel from many departments, including Maintenance. One upshot of that meeting was that maintenance personnel from NJDOT's Southern Region expressed interest in applying GASCAP to their operations and providing VTC with data for their routine maintenance activities.

A meeting was set up on April 25, 2013 with Maintenance Department personnel at the Southern Region office in Cherry Hill to discuss issues of translating maintenance activities into the equipment and material inputs used in GASCAP. The materials module of GASCAP is based on the item codes used on NJDOT contract bid sheets. From this meeting it became clear that additional changes to GASCAP were needed to facilitate data entry and to develop a procedure that would meet their needs. The primary issues to be resolved included:

- Identifying the material codes that correspond to crack sealing and pothole filling.
- Adding the capacity to handle on-road vehicles as construction equipment.
- Separating on-road vehicle emissions from idling and from travel.
- Eliminating the need for maintenance personnel to negotiate parts of the GASCAP module that are not relevant to routine maintenance activities.

A separate maintenance module was adopted as the best solution to these issues (the "Special Maintenance Module"). The module includes separate simplified equipment and materials components. The Southern Region Maintenance Department supplied a list of equipment and materials used for crack sealing and pothole filling. The list includes equipment and materials. Over the course of several meetings much useful input was received from Maintenance personnel. One important result is that the module was designed to allow maximum flexibility in terms of the units used to quantify material inputs.

<u>Equipment Types and Data</u>

The following six equipment types were included on the Maintenance Department list:

- Dump trucks
- Pickup trucks
- Pothole Killer truck
- Tar kettles

- SUVs
- Generators

With the exception of tar kettles and generators, all of the listed equipment types are on-road vehicles. MOVES runs used in the staging modules of GASCAP, are used to estimate the running emissions of all on-road vehicles handled by the Special Maintenance Module, as well as the idling emissions for larger trucks. Further discussions with Southern Region Maintenance staff, suggest that NJDOT passenger cars may be used to move managers and other personnel from the regional office to a specific job site. Crash cushion trucks are also used on maintenance projects as a safety measure. The Pothole Killer truck is a device that dispenses asphalt patching material, a mix of binder and aggregate, tack coat, and Detack, which is a dilute water-soluble, large hydrocarbon surfactant. Although it is not clear that they play any systematic role in maintenance daily operations, short and long haul combination trucks are included in the special module, should they ever be needed.

Dump trucks are modeled based on emissions estimates for Refuse trucks from MOVES. Similarly, the Pothole Killer trucks are modeled as Single Unit Short Haul trucks and the Crash Cushion trucks are modeled as Single Unit Long Haul trucks from MOVES. Idling emissions and running emissions are estimated for dump trucks, Pothole Killer trucks, crash cushion trucks, and long and short range combination trucks. Idling emissions for crash cushion trucks and Pothole Killer trucks are identical. This may represent an underestimate of emissions as Pothole Killer trucks heat materials and do mechanical work not done by crash cushion trucks. Since the heating of materials used in asphalt is estimated through the materials themselves and not the equipment, this is likely not a major shortcoming.

Pickup trucks are modeled as light commercial vehicles from MOVES. SUVs are modeled as passenger trucks, and passenger cars are modeled as passenger cars from MOVES. The Special Maintenance Module includes running emissions, but not idling emissions. . This represents a gap, because as a matter of practice the pickup trucks used for maintenance activities tend to idle most of the day when performing routine maintenance, according to Southern Region Maintenance personnel.

To account for pick-up truck idling, emissions were modeled in MOVES based on hourly pickup truck running emissions at an average speed of approximately zero. The model was run at the project level. Project level models in MOVES are limited to a single hour within either a weekday or a weekend day within a single month of a single year because of the intensity of processing at this level. The model averages emissions from urban and rural restricted and unrestricted roads for gasoline and diesel trucks for each model year for one vehicle of each fuel and model year combination for one hour at an average speed of 2.5 mph. Middlesex County was chosen as a surrogate for New Jersey. Temperature and humidity are estimated based on a June day in 2014, which is the last year for which the module has vehicle data. The model assumes a weekday between 10:00 to 10:59 AM.

Data on generators are available from the NONROAD model and were previously included in the equipment modules in GASCAP. There is an option to select tar kettles as an equipment type. This selection however resets the equipment section, redirects the user to the materials selection of the module and offers Rubberized Asphalt Joint Sealer as the material. It is done this way because the primary function of a tar kettle is to heat material for crack sealing, which is captured in the materials section.

Equipment Inputs

For all equipment type selections, except tar kettles, the Special Maintenance Module asks in turn for quantity, model year, and fuel type. For larger trucks including the Pothole Killer trucks, dump trucks, crash cushion trucks, and combination trucks, the Hours Idling and Miles Traveled textboxes, and the Air Conditioning checkbox are enabled. The running hours, and distance traveled textboxes are mandatory. The Air Conditioning checkbox allows the user to account for air conditioning used in the vehicle. For other vehicles, including pickup trucks, SUVs, and passenger cars the Miles Traveled textbox is enabled and mandatory. The user may also indicate whether the air conditioner was used. For generators, the Hours Used textbox and the Power Rating pulldown menu are enabled, but the air conditioning checkbox is not. The user must enter hours of use and the generator's power rating.

Error handling does not permit incomplete entries. However, at any point the user may abandon an entry by clearing the entry, with a Clear Entry button, selecting another equipment type, or selecting the material radio button.

Equipment Outputs

When an equipment line is entered the Special Maintenance Module reports direct and upstream emissions of CO_2, CH_4, and N_2O, as well as the CO_2 equivalence of direct HFC emissions from air conditioning and the upstream emissions of SF_6 from electricity generation. Black carbon particulate matter emissions are estimated for generator use and idling. The module also reports the input information including the equipment type, number of pieces, emissions type, i.e. Hours Used, Running Miles, or Hours Idling, and an associated value that quantifies it, a model year, fuel type, whether air conditioning was used, and power rating if a generator. Remove buttons are created so that the user can easily remove a single line of data.

Material Types and Data

The Maintenance Department list of materials used includes asphalt concrete patching material (binder and stone), asphalt rubber joint sealing material, and Detack – a dilute water-soluble hydrocarbon based surfactant. Six items are included in the materials portion of the Special Maintenance Module including:

- Asphalt Concrete Patching Material
- Binding Material for the Pothole Killer
- Rubberized Asphalt Joint Sealer
- Detack SP 3086
- Tack Oil
- Stone/Aggregate

The Pothole Killer is a truck with automated paving equipment. Based on a producer video,[34] the process is as follows. An air jet blows loose dust and other materials from the area to be repaired. A nozzle sprays the area with binder to bond the repair to the pavement. Asphalt concrete patching material is placed. Detack may be used to prevent the patching material from adhering to anything but the pavement. Aggregate is also used to provide a dry surface so that the road is immediately usable.

The specific items codes for each material are as follows:

- Asphalt Concrete Patching Material is modeled based on contract item code 159138M -- HMA Patch measured in tons. HMA Patch quantities may be input in tons (default) or pounds.
- Tack Oil and Binding Material for the Pothole Killer are modeled based on contract item code 401034M – Non-Solvent Tack Coat 76-22, pounds are the default unit, but input units may be tons or gallons.
- Stone/Aggregate is modeled using contract item code 302030P -- Soil Aggregate Base Course, Variable Thickness, which is measured in tons (default) but may also be measured in pounds or cubic yards.

Emissions from Detack are not estimated in GASCAP because they are not estimated in the models that GASCAP is based on. According to the company website, and Detack's Material Safety Data Sheet, the product is 85% water. The balance is a large hydrocarbon that is too specialized to be a simple product of petroleum refining, and is not used in motor vehicles, so it is not treated in the GREET models. A dummy entry was made to the material items worksheet that includes a description of "null" and a fictitious contract item code 000000A. This allows a user to enter a line in the data that records the amount of Detack used in gallons, but does not associate greenhouse gas emissions with the entry.

Crack sealing is done by applying rubberized asphalt sealer with a tar kettle. As discussed above, the only energy applied by the tar kettle is heat, which is captured through the heating emissions. The Rubberized Asphalt Joint Sealer is modeled based on contract item code 401024M -- Sealing of Cracks in Hot Mix Asphalt Surface Course, measured in pounds (default), tons, or gallons. The module converts feet to gallons at the rate 75 feet per gallon. This conversion rate is included in the Life-Cycle Maintenance Module.

Material Inputs

The pathways through the Materials section of the module depend on the particular material. For each material the appropriate input devices are enabled with defaults taken from the material items worksheet in GASCAP. Heating and ambient temperature, percentage of binder by weight in the mix, percent of moisture by weight in the aggregate, and the solvent type used, should cutback ever be needed, are all pull down menus. Quantity is input through a textbox. This textbox is enabled after every selection.

Selecting Asphalt Concrete Patching Material enables the heating and ambient temperature pull down menus and the percent binder and percent aggregate moisture pull down menus with defaults from the Material Items worksheet. The solvent pull down menu is not enabled.

Selecting Binding Material for the Pothole Killer enables the heating and ambient temperature pull down menus with defaults, but not the percent binder and percent aggregate moisture pull down menus. The solvent pull down menu is enabled to provide maximum flexibility, but non-solvent as the default.

Selecting Rubberized Asphalt Joint Sealer enables the heating and ambient temperature pull down menus with Material Items worksheet defaults, but not the percent binder and percent aggregate moisture pull down menus. The solvent pull down menu is enabled with non-solvent as the default.

Selecting Tack Oil enables the heating and ambient temperature pull down menus with defaults, but not the percent binder and percent aggregate moisture pull down menus or the solvent pull down menu.

Selecting Detack or Stone/Aggregate enables only the quantity.

Again, all enabled input devices are mandatory. However, at any point the user may abandon an entry by clearing the entry, with a Clear Entry button, selecting another equipment type, or selecting the material radio button.

Materials Outputs

When a material line is entered, the Special Maintenance Module reports direct and upstream emissions of CO_2, CH_4, and N_2O, as well as the upstream emissions of SF_6 from electricity generation. Black carbon particulate matter emissions are not estimated for materials. The module also reports the input information including the type of material, the amount, and the unit of measurement. In addition the heating temperature, percent binder, percent moisture in the aggregate, and any cutback are reported as indicated. Remove buttons are created so that the user can easily remove a single line of data.

Other Details of the Special Maintenance Module

A separate Results worksheet shows GHG emissions for equipment and materials broken down as Materials, Generators, Vehicle Idling and Vehicle Running. Project total emissions are also reported. As in the rest of GASCAP, emissions may be reported in grams or metric tons, except that SF_6 emissions are reported in milligrams and kilograms.

A Save button on the data entry page saves the detail lines and the Results Page to a separate workbook. It saves only the project values so it is not editable in that sense. The Reset button clears all data from the module. The View Detailed Results button on the data entry worksheet and any one of four Return to Data Entry buttons on results worksheet allow a user to navigate between the two pages. Project totals are also shown at the top of the data entry worksheet to the right of the input form. Buttons have been added to this and other modules to allow users to access this and other modules in GASCAP.

Third Applied Case Study

After several training sessions during which the special maintenance module was tested extensively, maintenance personnel from NJDOT’s Southern Region provided nine cases as a test of the module. These included three each for crack sealing, pothole killer use, and manual patching. Results for each type of maintenance activity are shown in Volume II Appendix E. No generator powered lighting was used.

During the course of analyzing the data one error was found. Equipment emissions were not properly quantified and were expressed as either one hour of idling or one running mile because of an error in the code. The error has been fixed and the output has been manually corrected. This is possible because the number or miles or hours is recorded in the detailed output.

As discussed above idling emissions were not estimated for pickup trucks. Various assumptions were used to estimate idling emissions as detailed above. Pickup trucks are significant equipment inputs for crack sealing and manual patch operations. Typically the number of miles traveled is small and the number of working hours when pickup trucks are normally idling is considerable. As a result idling emissions are usually one and often two orders of magnitude larger than running emissions.

Crack Sealing

On the basis of the three cases provided, crack sealing operations typically include a pickup truck, a tar kettle, and one or two crash cushion trucks. The distance covered in a day is a mile or less but idling is between six and ten hours. Air conditioning was used in all but one of the vehicles reported. All vehicles used diesel. Model years were from 1999 to 2007. The materials used include joint sealant, which is transported in a pickup truck and heated in a tar kettle. Detack may be used. In the second and third cases 814 pounds and 980 pounds of joint sealant were used, respectively. The first case includes placement of more than a ton (3,450 pounds) of joint sealant and eight gallons of Detack. Combined results of the three crack sealing case studies are shown in Table 38.

Table 38 - Combined GHG emissions from three crack sealing case studies

Crack Sealing (Three Cases)

	Direct Materials	Upstream Materials	Combined Materials		Direct Idling	Upstream Idling	Combined Idling
g CO2e	61,641	1,822,331	1,883,973	g CO2e	602,273	172,708	774,982
% Materials	3.27%	96.73%		% Idling	77.71%	22.29%	
% Combined Total			70.56%	% Combined Total			29.03%

	Direct Running	Upstream Running	Combined Running		Direct Total	Upstream Total	Combined Total
g CO2e	8,768	2,135	10,903	g CO2e	672,682	1,997,175	2,669,857
% Running	80.42%	19.58%		% Total	25.20%	74.80%	
% Combined Total			0.41%	% Combined Total			100%

Table 38 shows that 70% of GHG emissions are from materials and the balance is from vehicle idling and running. Most emissions (75%) are upstream emissions. This is to be expected because the principal material used is a modified form of asphalt binder, the production of which makes the upstream share of asphalt concrete roughly half of all emissions that result from asphalt manufacturing and placement. Idling and running emissions are more than three quarters direct emissions. These findings are consistent with the Route 35 reconstruction and the Route 47 resurfacing case studies also included in this report. Upstream emissions were nearly 75% of total emissions. These three cases account for nearly a metric ton per day of CO_2 equivalence.

Manual Patch

The equipment for manual patching operations includes a device to heat asphalt concrete and a crash cushion truck. Air conditioning was used in all vehicles. One case used 0.1 tons of HMA heated to 325°F, while the others used emulsion binders and aggregate (130°F – 140°F). One case used a pickup truck. Two of the operations were of short duration (0.5 hours and 1.0 hours). The other case was of longer duration (8.0 hours). Combined results of the three manual patch case studies are shown in Table 39.

Table 39 - Combined GHG emissions from three manual patch case studies

Manual Patch (Three Cases)							
	Direct Materials	Upstream Materials	Combined Materials		Direct Idling	Upstream Idling	Combined Idling
g CO_2e	9,394	59,162	68,556	g CO_2e	258,662	75,858	334,520
% Materials	13.70%	86.30%		% Idling	77.32%	22.68%	
% Combined Total			16.71%	% Combined Total			81.54%
Direct Running	Upstream Running	Combined Running	Combined Running		Direct Total	Upstream Total	Combined Total
g CO_2e	5,743	1,417	7,160	g CO_2e	273,799	136,437	410,236
% Running	80.21%	19.79%		% Total	66.74%	33.26%	
% Combined Total			1.75%	% Combined Total			100%

The manual patch cases are much smaller operations than the crack sealing cases on average accounting for less than 0.05 MT of CO_2 equivalence per day. Two of these cases took an hour or less. However, crash cushion trucks were required to idle while patching material was heated and placed. As a result, materials account for roughly 17% of GHG emissions, and running and idling emissions constitute the balance.

Pothole Killer

Pothole killer operations include blowing debris from the area to be repaired with an air jet, spraying tack oil to enable bonding of the repair, spraying asphalt concrete to fill the hole, and spraying course aggregate to provide a dry surface so that the facility need not be closed to traffic. Material inputs are expected to include tack oil, HMA patch or binder plus aggregate, and dry aggregate or Detack.

The analysis was conducted by Maintenance Department personnel at the Southern Region office in Cherry Hill. The material inputs were inconsistent with what we assumed was needed to estimate emissions from the Pothole Killer. In all three cases there is only one material input, instead of the three typically used. In the first and third case the material is “binding material for Pothole Killer,” which is asphalt binder with no aggregate. In the second case the material is “asphalt concrete patching material,” which is HMA. The heating temperatures vary from 70°F to 145°F, which is within the expected range.

Equipment used in the three case studies include one Pothole Killer truck and one crash cushion truck. Running and idling emissions are estimated for all vehicles. Idling hours vary from four to eight hours. All vehicles were diesel with model years from 1999 to 2000. Air conditioning was used by all vehicles.

Due to the uncertainties as to whether the material inputs are correct for these case studies we do not report an analysis of the results. The full outputs are shown in Volume II Appendix E.

Fourth Case Study Showing Fuel Consumption Embodied in Paving Materials

This brief case study presents differences in the price of the embodied fuel consumption of paving materials and the wholesale prices of those materials. Fuel consumption was inputted from GASCAP and its supporting documents with some supplementation from the original sources. Table 40 shows the price and the cost of energy embodied in a ton of aggregate, cement, asphalt binder, and reinforcing steel.

Table 41 compares the embodied energy cost and wholesale price of one short ton of unreinforced concrete pavement, reinforced concrete pavement of the same volume, and one short ton of hot mix asphalt pavement. The concrete pavements are assumed to include 16% cement and 84% coarse and fine aggregates. The reinforced concrete weighs slightly more than one ton because of the higher density of the rebar, but it has the same volume as the unreinforced concrete. The asphalt pavement is assumed to include 5% binder with 4% moisture in the aggregate. The weight of the unmixed materials to produce one ton of asphalt pavement reflects the moisture which is lost during mixing.

Table 40 - Embodied energy and wholesale price of paving materials

AGGREGATE (per ton)	MMBtu	LHV (MMBtu)	Basis	Total	Unit Price	Cost for Fuel Type	Energy Cost	Wholesale Price
Coal	8.048E-04	19.5463	ton	4.118E-05	35.61	$0.001	$0.553	$35.00
Diesel	1.798E-02	0.12845	gallon	1.400E-01	3.5464	$0.496		
Natural Gas	4.424E-03	1	MMBtu	4.424E-03	3.692	$0.016		
Gasoline	1.422E-03	0.11609	gallon	1.225E-02	3.17552	$0.039		
Electricity	1.307E-02	0.003414	kWh	3.828E+00	0.067	$0.256		
ASPHALT BINDER (per ton)	MMBtu	LHV (MMBtu)	Basis	Total	Unit Price	Cost for Fuel Type	Energy Cost	Wholesale Price
Diesel	4.079E-01	0.12845	gallon	3.175E+00	3.5464	$11.261	$25.289	$545.00
Natural Gas	1.631E+00	1	MMBtu	1.631E+00	3.692	$6.023		
Electricity	4.079E-01	0.003414	kWh	1.195E+02	0.067	$8.005		
CEMENT (per ton)	MMBtu	LHV (MMBtu)	Basis	Total	Unit Price	Cost for Fuel Type	Energy Cost	Wholesale Price
Coal	3.456E-01	19.5463	ton	1.768E-02	35.61	$0.630	$26.417	$105.95
Petroleum coke	8.810E-02	25.37	ton	3.473E-03	68.719188	$0.239		
Natural Gas	3.030E-02	1	MMBtu	3.030E-02	3.692	$0.112		
Diesel	4.559E-03	0.12845	gallon	3.550E-02	3.5464	$0.126		
Residual Oil	4.481E-04	0.1403525	gallon	3.193E-03	2.201	$0.007		
Gasoline	5.302E-04	0.11609	gallon	4.567E-03	3.17552	$0.015		
LPG	3.257E-05	0.08495	gallon	3.834E-04	2.55	$0.001		
Waste Fuels	4.661E-02				0	$0.000		
Electricity	6.076E-02	0.003414	kWh	1.780E+01	0.067	$1.192		
REINFORCING STEEL (per ton)	MMBtu	LHV (MMBtu)	Basis	Total	Unit Price	Cost for Fuel Type	Energy Cost	Wholesale Price
Residual. oil	1.219E+00	0.07472	gallon	1.632E+01	2.201	$35.911	$111.223	$580.60
Gasoline	1.086E-03	1	MMBtu	1.219E+00	3.692	$4.501		
Diesel	1.430E-02	0.12845	gallon	8.456E-03	3.5464	$0.030		
Natural Gas	2.581E+00	1	MMBtu	2.581E+00	3.692	$9.529		
Coal	5.857E+00	19.5463	ton	2.997E-01	35.61	$10.671		
Electricity	2.577E+00	0.003414	kWh	7.549E+02	0.067	$50.582		

These results show that less energy and fewer funds are required to produce one ton of asphalt pavement than either of the concrete pavements, and that reinforcing with steel increases the cost and the embodied energy in concrete pavement. Although the areas that could be covered by each of the pavement designs are not directly comparable, results in Table 41 suggest strongly that GASCAP GHG emissions output, based on alternative pavement designs reflects embodied energy in construction materials and cost.

Table 41 - Embodied energy cost and wholesale prices for materials used in paving designs

Portland Cement Concrete - Unreinforced (per ton)	Proportion	Energy Price	Price
Cement	16.0%	$4.23	$16.95
Aggregate	84.0%	$0.46	$29.40
Total	100.0%	$4.69	$46.35
Portland Cement Concrete - Reinforced (per ton)	Proportion	Energy Price	Price
Cement	15.9%	$4.20	$16.83
Aggregate	83.4%	$0.46	$29.19
Reinforcing Steel	0.7%	$0.80	$4.19
Total	100.0%	$5.46	$50.21
Hot Mix Asphalt (per ton)	Proportion	Energy Price	Price
Binder	5.0%	$1.32	$5.30
Aggregate *	99.0%	$0.55	$34.64
Total	104.0%	$1.87	$39.93

* Reflects 4% moisture in the Aggregate

CONCLUSIONS AND FUTURE RESEARCH

This final report documents the various upgrades and improvements made to the GASCAP software. The software is now largely complete and can be used by NJDOT staff and others to conduct assessments of the life-cycle GHG emissions associated with construction and maintenance activities. The case studies conducted as part of this research provide useful guidance on the likely results of any analysis. The choice and quantity of materials used in a project accounts for the bulk of GHG emissions associated with construction activities. Choices on how a project is staged, and how this affects the flow of traffic either through or around a worksite can also have a large influence on the total GHG emissions associated with a project. The primary fuel consumption of equipment on a project tends to be a small component of total emissions, however, for some maintenance activities this may be more important, as demonstrated in our applied maintenance case study.

While this phase of the research is complete, there remain various enhancements to GASCAP that can be made. The software was designed to be user-friendly and this led to the decision to develop this in Microsoft Excel. This is a useful platform for handling the emissions factors data that drive the calculation of GHG emissions. However, at this point the complexities make this format more cumbersome for future development and for identification of any errors or bugs in the software. Future development should therefore include the migration of GASCAP to a more flexible software environment.

In conducting the case studies we identified various elements that should be upgraded in the future. In the materials module, despite the large effort to include item bid sheet codes with detailed geometric information on components, some were missing. This is likely due to continual changes in vendor specifications and updating of the bid sheet databases. While this was a minor component of total GHG emissions, our case study showed that some components do account for non-trivial GHG emissions and certainly as a fraction of total GHG emissions associated with materials. Furthermore, the process of inputting the bid sheet items into GASCAP is time consuming and methods to input bid sheet codes electronically would be a substantial improvement, but would work best if NJDOT could provide this information in a database format (as opposed to pdf files).

As part of this research we spent considerable effort to find studies that could provide information on equipment activity at construction sites. In the end, we used California data from a survey of equipment activity conducted in 2005. This study is the best available information and is used by other research teams. Our case study suggests that the equipment emissions are small relative to other sources of emissions. Whether this is due to an underestimation of equipment activity is not known, however, as a check on our assumptions, the amount of fuel consumed appears reasonable. Despite this, much more research is needed to develop better equipment activity profiles. We see two possibilities for future research in this area. According to NJDOT staff, contractors are required to log their fuel usage in order to adjust contracted amounts for changes in fuel prices at the completion of their work. From our understanding, NJDOT has this data for contracted projects. We were unable to obtain this data from NJDOT staff, but analysis of this data could provide general classifications of fuel consumption (and consequent GHG emissions) associated with different project types and the size of those projects. The second approach would be a large study that records the detailed equipment activity and fuel consumption from a large sample of construction projects. The latter approach would allow one to record the actual time that equipment is in various operating modes and the engine loads over the course of the entire project.

The life-cycle maintenance module is based on a fixed maintenance plan for pavements provided by NJDOT staff. We were unable to obtain a similar maintenance plan for bridges. Given the large variety of different bridge types this is a challenging task, but could be done at least for common bridge types and culverts. The maintenance module could also be substantially improved by adding flexibility to maintenance decisions and by taking into consideration how the deterioration of the road surface can increase the fuel consumption of vehicles using the road (and consequently increase GHG emissions). We see this as a priority area for further research. Some investigation of how to do this was conducted, but resource constraints prevented this from being implemented.

Another priority area is to conduct additional case studies. Our case study results provide useful information for understanding which components of a project account for most of the GHG emissions. However, more case studies are needed to generalize these findings. The case study process is also useful for testing the user-friendliness of the software and identifying any information that might be missing. The case studies also provide an opportunity to work closely with NJDOT engineering staff and to train them in the use of GASCAP.

The GASCAP software will be made publically available at www.gascap.org. A condition of using the software will be that any research teams or NJDOT staff that use it, provide us with both feedback on their experience and their case study results. This will allow us to compile a database of results but also to identify future improvements to the software.

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