Addressing Transportation Agency Challenges in Improving Climate Resilience: Two Tools from FHWA

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Word count: 4,486 words text + 3 Tables and 7 Figures (2,500) = 6,986 words

Submission date: August 1, 2014
ABSTRACT

Transportation agencies are experiencing changes in extreme weather events, and will face increased climate and weather risks in the future, in the form of changing extreme precipitation, heat waves, sea level rise, and other stressors. Transportation agencies are becoming increasingly aware of the need to plan for the impacts of these changes, yet have struggled with how to do so in the face of uncertainty and finite resources. For example, acquiring and processing locally-relevant climate information has proved challenging. Participants in the U.S. Department of Transportation (DOT) Gulf Coast Study, Phase 2 have been working to understand and address the challenges that transportation agencies face in increasing their resilience to climate change. This paper focuses on two tools developed under this study that address a major challenge that transportation agencies face in adapting to climate change. The first, the CMIP Climate Data Processing Tool, provides an easy way to gather and process downscaled climate model data, and “translates” that data into information relevant to transportation engineers and planners. The second tool, the Vulnerability Assessment Scoring Tool (VAST), provides a framework for assessing vulnerability in a transparent, cost-effective way. These tools significantly advance the state of the practice for transportation agencies to respond to climate change impacts, and beta-versions have been used successfully by several state DOTs and Metropolitan Planning Organizations (MPOs). This paper presents information about these tools, examples of how they can be applied within transportation agencies, and areas for future research and development.
INTRODUCTION AND PURPOSE

The United States is experiencing changes in climate, in the form of higher average and extreme temperatures, changes in precipitation patterns, sea level rise, and changes in extreme weather events. These changes are already occurring, and projected to continue or worsen in the future (1, 2, 3). Transportation agencies are grappling with these changes, which could threaten the infrastructure investments and operational continuity on the nation’s roads and waterways (4).

The United States Department of Transportation, through its Gulf Coast Study, Phase 2 (GC2) has been working to identify and address the challenges that transportation agencies face to increase their resilience to climate change. The study used Mobile, Alabama as a pilot city to develop and test methodologies for transportation agencies to identify their vulnerabilities to climate change and take action to address them. The study identified several challenges that transportation agencies face in this area. This paper focuses on two of these challenges, and two tools developed during the study to help agencies overcome them.

The first challenge, and a major one that transportation agencies face, is translating climate projections into potential impacts on transportation systems, and using the information to inform engineering and planning decisions (4, 5). Often, readily-available climate projections take the form of changes in average temperatures and precipitation amounts, which are informative but do not tie directly into transportation decisions.

A second challenge for transportation agencies is assessing vulnerability in a transparent, cost-effective way. Agencies need ways to identify their most pressing vulnerabilities in order to prioritize resources for further analysis where needed or begin to adopt “no regrets” strategies to increase resilience. This paper focuses on two tools developed under GC2 to help overcome these challenges. The first, the CMIP Climate Data Processing Tool, processes readily-available, downscaled climate data at the local level into 59 specific, transportation-oriented temperature and precipitation variables. The second, the Vulnerability Assessment Scoring Tool (VAST), provides a framework for users to conduct a vulnerability screen of their assets. The tools are available on the FHWA website at http://www.fhwa.dot.gov/environment/climate_change/adaptation/adaptation_framework/modules/index.cfm?moduleid=4.

The study also developed two additional resources. The Transportation Climate Change Sensitivity Matrix documents known effects of 11 climate stressors (from temperatures to dust storms) on six transportation modes, including specific infrastructure types and operations. For each relationship, the Matrix describes the relationship, relevant thresholds, potential sensitivity indicators, key resources, and other notes. Finally, Assessing Criticality in Transportation Adaptation Planning is a guide to help transportation agencies determine how to focus their vulnerability assessments on the most critical components, if needed.

These tools significantly advance the state of the practice for transportation agencies to respond to climate change impacts, and beta-versions have been used successfully in several state DOTs and MPOs. They are freely accessible, easy to use, and scalable, in that users can use them over time as resources allow. This paper presents information about the CMIP Climate Data Processing Tool and VAST, examples of how they can be applied within transportation agencies, and areas for future research and development.

CMIP CLIMATE DATA PROCESSING TOOL

Purpose

The CMIP Climate Data Processing Tool is designed to allow users to access local-level, practical climate projections. Its outputs are tailored to transportation decision-makers, and addresses the need to access and interpret climate information necessary to understand how climate change may affect transportation systems. As an Excel-based tool, it is accessible to transportation agency staff.

GC2 devoted substantial time and resources to developing downscaled climate projections for Mobile and processing that information into specific derived variables. Derived variables are temperature...
and precipitation variables calculated from climate model outputs of daily minimum temperature, 
maximum temperature, and precipitation. For example, average number of days per year above 95°F or 
average seasonal rainfall are variables that can be derived from daily climate model data. The derived 
variables developed under GC2 were very useful for conducting more detailed, engineering-based 
vulnerability assessments, but the time and effort spent processing the climate information to derive those 
variables would likely be cost-prohibitive in most circumstances. The CMIP Climate Data Processing 
Tool is designed to provide those derived variables in a matter of hours. The information can then be used 
to inform transportation vulnerability assessments and resilience planning.

Methodology

The CMIP Climate Data Processing Tool works with data from the U.S. Bureau of Reclamation’s 
Downscaled CMIP3 and CMIP5 Climate and Hydrology Projections (DCHP) database (explained in 
more detail under Inputs, below). Users request and download the data—choosing their own location, 
climate models, and emissions scenarios—and after entering some basic information into the tool 
interface, press a “Process Data” button that will calculate 59 derived variables, described in more detail 
under Outputs, below).

Inputs

The CMIP Climate Data Processing Tool is currently designed to work exclusively with data from the 
U.S. Bureau of Reclamation’s Downscaled CMIP3 and CMIP5 Climate and Hydrology Projections 
(DCHP) database. This database provides climate model data from the Coupled Model Intercomparison 
Project phase 3 (CMIP3) and phase 5 (CMIP5). CMIP3 and CMIP5 are products of the World Climate 
Research Programme (WCRP), and are the climate model simulations used in the United Nations' 
Intergovernmental Panel on Climate Change (IPCC) Fourth and Fifth Assessment Reports, respectively. 
CMIP3 and CMIP5 are global datasets, and there are several ways to access these data, including from the 
WCRP directly. The DCHP website was chosen for this tool because it provides peer-reviewed data 
downscaled (at a higher spatial resolution), for a wide range of models and emissions scenarios, and in an 
Excel-ready format, which makes it easier for transportation agencies to work with.

The climate models available on the DCHP website are summarized in Table 1. The data have 
been downscaled using a daily bias-correction and constructed analogs (BCCA) technique to 1/8 degree 
grids (each approximately 56 square miles) covering the continental United States and parts of southern 
Canada (6). CMIP3 data are available on the daily timescale for the periods 1961-2000, 2046-2065, 2081- 
2100, and CMIP5 data are available on the daily timescale from 1950-2099, and users can specify their 
own baseline and future time periods. The DCHP database also provides observed temperature and 
precipitation data from 1950-1999 on the same grid (7).

The DCHP website provides CMIP3 data for emission scenarios B1, A1B, and A2 (low, medium-
high, and medium-high emissions, respectively), and CMIP5 data for Representative Concentration 
Pathways (RCP) 2.6, 4.5, 6.0, and 8.5 (emissions reductions, stabilization, higher stabilization, and high 
emissions, respectively).

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**Table 1: Climate Models Available through DCHP Database**

<table>
<thead>
<tr>
<th>CMIP3</th>
<th>CMIP5</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Bjerknes Center for Climate Research, Norway (BCCR-BCM2.0)</td>
<td>• Commonwealth Scientific and Industrial Research Organization and Bureau of Meteorology, Australia (ACCESS1-0, ACCESS1-3)</td>
</tr>
<tr>
<td>• Canadian Centre for Climate Modeling and Analysis, Canada (CGCM3.1)</td>
<td>• Beijing Climate Center, China Meteorological Administration (BCC-CSM1-1, BCC-CSM1-1-M)</td>
</tr>
<tr>
<td>• Meteo-France/Centre National de Recherches Meteorologiques, France (CNRM-CM3)</td>
<td>• College of Global Change and Earth System Science, Beijing Normal University (BNU-ESM)</td>
</tr>
<tr>
<td>• Commonwealth Scientific and Industrial Research Organization, Atmospheric Research, Australia (CSIRO-Mk3.0)</td>
<td>• Canadian Centre for Climate Modelling and Analysis (CanESM2)</td>
</tr>
<tr>
<td><strong>CMIP3</strong></td>
<td><strong>CMIP5</strong></td>
</tr>
<tr>
<td>-----------</td>
<td>-----------</td>
</tr>
<tr>
<td>- U.S. Dept. of Commerce/NOAA/Geophysical Fluid Dynamics Laboratory, USA (GFDL-CM2.0, GFDL-CM2.1))</td>
<td>- National Center for Atmospheric Research (CCSM4)</td>
</tr>
<tr>
<td>- NASA/Goddard Institute for Space Studies, USA (GISS-ER)</td>
<td>- Community Earth System Model Contributors (CESM1-BGC, CESM1-CAM5)</td>
</tr>
<tr>
<td>- Institute for Numerical Mathematics, Russia (INM-CM3.0)</td>
<td>- Centro Euro-Mediterraneo per I Cambiamenti Climatici (CMCC-CM)</td>
</tr>
<tr>
<td>- Institut Pierre Simon Laplace, France (IPSL-CM4)</td>
<td>- Centre National de Recherches Météorologiques/Centre Européen de Recherche et Formation Avancée en Calcul Scientifique (CNRM-CM5)</td>
</tr>
<tr>
<td>- Center for Climate System Research (The University of Tokyo), National Institute for Environmental Studies, and Frontier Research Center for Global Change, Japan (MIROC3.2(medres))</td>
<td>- Commonwealth Scientific and Industrial Research Organization, Queensland Climate Change Centre of Excellence (CSIRO-Mk3-6-0)</td>
</tr>
<tr>
<td>- Meteorological Institute of the University of Bonn, Meteorological Research Institute of the Korean Meteorological Association, Germany/Korea (ECHAM-G)</td>
<td>- EC-Earth consortium, representing 22 academic institutions and meteorological services from 10 countries in Europe (EC-EARTH)</td>
</tr>
<tr>
<td>- Max Planck Institute for Meteorology, Germany (ECHAM5/MPI-OM)</td>
<td>- Laboratory of Numerical Modeling for Atmospheric Sciences and Geophysical Fluid Dynamics, Institute of Atmospheric Physics, Chinese Academy of Sciences, and Center for Earth System Science, Tsinghua University (FGOALS-g2)</td>
</tr>
<tr>
<td>- Meteorological Research Institute, Japan (MRI-CGCM2.3.2)</td>
<td>- Laboratory of Numerical Modeling for Atmospheric Sciences and Geophysical Fluid Dynamics, Institute of Atmospheric Physics, Chinese Academy of Sciences (FIO-ESM)</td>
</tr>
<tr>
<td>- National Center for Atmospheric Research, USA (CCSM3)</td>
<td>- The First Institute of Oceanography, State Oceanic Administration, China (FIO-ESM)</td>
</tr>
<tr>
<td>- National Center for Atmospheric Research, USA (PCM)</td>
<td>- NOAA Geophysical Fluid Dynamics Laboratory (GFDL-CM3, GFDL-ESM2G, GFDL-ESM2M)</td>
</tr>
<tr>
<td>- Hadley Centre for Climate Prediction and Research/Met Office, UK (UKMO-HadCM3)</td>
<td>- NASA Goddard Institute for Space Studies (GISS-E2-H-CC, GISS-ER-R, GISS-ER-R-CC)</td>
</tr>
<tr>
<td></td>
<td>- Met Office Hadley Centre (additional HadGEM2-ES realizations contributed by Instituto Nacional de Pesquisas Espaciais) (HadGEM2-AO, HadGEM2-CC, HadGEM2-ES)</td>
</tr>
<tr>
<td></td>
<td>- Institute for Numerical Mathematics (INM-CM4)</td>
</tr>
<tr>
<td></td>
<td>- Institut Pierre-Simon Laplace (IPSL-CM5A-LR, IPSL-CM5A-MR, IPSL-CM5B-LR)</td>
</tr>
<tr>
<td></td>
<td>- Japan Agency for Marine-Earth Science and Technology, Atmosphere and Ocean Research Institute (The University of Tokyo), and National Institute for Environmental Studies (MIROC-ESM, MIROC-ESM-CHEM)</td>
</tr>
<tr>
<td></td>
<td>- Atmosphere and Ocean Research Institute (The University of Tokyo), National Institute for Environmental Studies, and Japan Agency for Marine-Earth Science and Technology (MIROC5)</td>
</tr>
<tr>
<td></td>
<td>- Max-Planck-Institut für Meteorologie (Max Planck Institute for Meteorology) (MPI-ESM-LR, MPI-ESM-MR)</td>
</tr>
<tr>
<td></td>
<td>- Meteorological Research Institute (MRI-CGCM4)</td>
</tr>
<tr>
<td></td>
<td>- Norwegian Climate Centre (NorESM1-M, NorESM1-ME)</td>
</tr>
</tbody>
</table>
The data come from the DCHP website in the form of tables with daily precipitation (precip), minimum surface air temperature (Tmin), and maximum surface air temperature (Tmax) for each climate model and emissions scenario selected (see Figure 1).

FIGURE 1 Example of downscaled CMIP5 daily precipitation data accessible from the DCHP website – daily precipitation values (in millimeters) are provided for each from 1950 through 2099 for each climate model/emission scenario download (represented by columns D-O).

Once the user follows tool instructions to request data for up to four climate model grid cells from the DCHP database, they enter basic information into the tool’s input screen about the data they downloaded, to help the tool find and process the information properly. The final step for the user is to press the “Process Data” button, which will launch the calculations necessary to generate the tool outputs.

Outputs
The CMIP Climate Data Processing Tool outputs the observed baseline value, modeled baseline value, modeled future value, and other information for 59 derived variables (shown in Table 2). This list of variables was developed as part of the Gulf Coast Study through interviews with transportation engineers and climate scientists to align, to the extent possible, the variables engineers need to inform their decisions with the variables climate models can provide (8). For example, and as highlighted in Table 2, designs of asphalt pavement binders are based on expected 7-day average temperatures and absolute minimum temperatures. This tool generates these two variables from the raw climate model temperature
data, so that users can identify whether the temperature thresholds used for in their current pavement designs may be exceeded in the future.

### TABLE 2 CMIP Climate Data Processing Tool Output Variables

<table>
<thead>
<tr>
<th>Category</th>
<th>Derived Variables</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temperature</td>
<td>Average annual daily mean, minimum, and maximum temperature</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Average summer and winter temperature</td>
<td></td>
</tr>
<tr>
<td>Extreme Heat</td>
<td>Hottest temperature of the year</td>
<td></td>
</tr>
<tr>
<td></td>
<td>95&lt;sup&gt;th&lt;/sup&gt; and 99&lt;sup&gt;th&lt;/sup&gt; percentile temperatures</td>
<td>Thresholds selected because identified as having operational impacts, as well as being easy to communicate</td>
</tr>
<tr>
<td></td>
<td>Number of days per year above baseline 95&lt;sup&gt;th&lt;/sup&gt; and 99&lt;sup&gt;th&lt;/sup&gt; percentile temperatures</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Number of days per year and season above 95°F, 100°F, 105°F, and 110°F</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Maximum number of consecutive days per year above baseline 95&lt;sup&gt;th&lt;/sup&gt; and 99&lt;sup&gt;th&lt;/sup&gt; percentile temperatures, 95°F, 100°F, 105°F, and 110°F</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Highest 4-day average temperatures</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Highest 7-day average temperatures</td>
<td>Temperature variable used for asphalt pavement binder design</td>
</tr>
<tr>
<td>Extreme Cold</td>
<td>Coldest temperature of the year</td>
<td>Temperature variable used for asphalt pavement binder design</td>
</tr>
<tr>
<td></td>
<td>1&lt;sup&gt;st&lt;/sup&gt; and 5&lt;sup&gt;th&lt;/sup&gt; percentile temperatures</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Lowest 4-day average temperatures</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Lowest 7-day average temperatures</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Number of days per year below freezing</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Average number of times minimum temperatures fluctuate around freezing</td>
<td>Proxy for changes in freeze-thaw cycles</td>
</tr>
<tr>
<td>Precipitation</td>
<td>Total annual precipitation</td>
<td></td>
</tr>
<tr>
<td></td>
<td>95&lt;sup&gt;th&lt;/sup&gt; and 99&lt;sup&gt;th&lt;/sup&gt; percentile 24-hour precipitation</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Number of days with precipitation above baseline 95&lt;sup&gt;th&lt;/sup&gt; and 99&lt;sup&gt;th&lt;/sup&gt; percentile precipitation</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Total seasonal precipitation</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Largest 3-day precipitation event per season</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Annual maximum precipitation (time series)</td>
<td>Can be used to estimate 24-hour precipitation recurrence intervals by applying extreme value distribution</td>
</tr>
</tbody>
</table>

The projected values for all variables are calculated using the same general process, summarized in Figure 2. First, for each model, the tool averages daily Tmax, Tmin, and Precip across grid cells to get a value for each model, for each day (stage 1 in Figure 2). Next, the tool calculates the variable for each year for each model (stage 2), and then averages across years (stage 3) within the given 20-30 year climate period (e.g., 1961-2000, 2046-2065, or 2081-2099 if using CMIP3 data or user-defined periods if...
using CMIP5 data). Then, the tool calculates the multi-model ensemble average projections for each time period by taking the average values for each climate period across models (stage 4).

Then, the tool calculates the change from baseline (modeled value minus modeled baseline) using the multi-model ensemble means. Finally, the tool adds the change in baseline to the baseline observed value to derive the “projected value” for each variable. This step helps contextualize the climate model projections in the specific location, and corrects for whether certain models run generally hotter, cooler, wetter, or drier.

Ultimately, the tool provides the following information for each variable listed in Table 2, as shown in Figure 3.

For the baseline time period:
- Baseline Observed Value – Value calculated using the observed data downloaded from the DCHP website. Users may also override this value with observed data from a local weather station, if desired.
- Baseline Modeled Value – Value for the baseline time period calculated based on climate model data

For future time periods:
- Projected Value – Change from Baseline + Observed Value
- Change from Baseline – Change in value from modeled baseline to modeled future period (Note: modeled future period value not shown on Output sheet, but available within the tool)
- % Change from Observed – Change from Baseline / Observed Value
- Model Uncertainty Range – The confidence interval range for the projected value across all models, using a Student’s T distribution for the user-specified confidence interval (e.g., 95%). The confidence interval is calculated for the projected change to determine the range of changes, which are then added to the observed value to show a range in projected values.
### Applications

The outputs of the CMIP Climate Data Processing Tool can be used for applications as would any climate model projections.

For example, they can be used to inform a vulnerability assessment, to determine whether the asset or system under study would be vulnerable to the potential changes. Users can compare the specific variables against known thresholds to aid in that vulnerability assessment. For example, average 7-day maximum temperature is a variable used for the design of asphalt pavement binders. If users know the 7-day maximum atmospheric temperature threshold used in their pavement binder (e.g., 108°F for PG 64-22 in Mobile, Alabama (8)), they can identify whether climate models indicate this threshold may be exceeded in the future and whether additional investigation is needed into pavement binder selection.

The projections can also be used to inform engineering analyses of asset vulnerability. While climate model projections are not meant to provide a single target for a design, they can provide a reasonable range of future values that can be used in sensitivity analyses or Monte Carlo analyses that can aid decision-making. For example, the U.S. DOT analyzed several scenarios of modeled 24-hour hour precipitation return intervals (across models, emissions scenarios, and time periods) to study the vulnerability of a specific culvert to climate change (9). The 2-, 5-, 10-, 25-, 50-, and 100-year storms were estimated from the climate models using a Gaussian extreme value distribution (8), as could be done using the time series of annual maximum 24-hour precipitation from the CMIP Climate Data Processing Tool. Then the range of potential precipitation values were plugged into hydrologic and hydraulic models—the U.S. Department of Agriculture (USDA)-Natural Resources Conservation Service (NRCS) WinTR-20 program (10) and the FHWA HY-8 Version 7.2 program, respectively—to model potential inundation areas under each scenario. This supported an analysis of the costs and benefits of hypothetical adaptation options (9).

### Areas for Future Research and Development

The dialogue between transportation engineers and climate scientists is ongoing. As this conversation evolves, and the community of practice in transportation adaptation identifies additional derived variables that would be helpful, these could be added to the tool. For example, extreme precipitation is still an area where more work is needed to identify how climate models outputs can be processed or tailored in ways...
to meet the needs of engineers. The tool currently provides 95th and 99th percentile precipitation values, along with a time series of annual maximum precipitation values. Freeze-thaw cycles, snowfall, and wildfire are other areas for future development of derived variables. Future research could also be done to understand how to best couple climate model outputs to watershed model inputs. More work could be done to more closely align the outputs of climate data processing with variables familiar to transportation engineers.

Finally, in addition to expanding or otherwise improving the set of derived variables, additional research and development may be needed to allow the tool (or similar tools) to accommodate other sources of climate data. For example, transportation agencies may prefer to use non-downscaled data, data covering a larger geographic area (the tool focuses on local-level assessments), or data from a local university. The same principles and processing techniques in the tool could be applied to any daily climate data.

VULNERABILITY ASSESSMENT SCORING TOOL

Purpose
The Vulnerability Assessment Scoring Tool (VAST) is a resource to help transportation agencies tackle another challenge associated with adapting to climate change—how to conduct a vulnerability assessment or otherwise narrow the field of possible areas to address. VAST provides a structured framework to help a user conduct an indicator-based vulnerability assessment or screen, whereby a user identifies characteristics of their assets or systems that could serve as indicators of their vulnerability. An indicators approach allows for a vulnerability assessment that leverages available data (or facilitates collection of data), and is transparent in its approach (11, 12, 13).

VAST does not provide any “default” information about particular assets or their vulnerability, or even indicators to use. Rather, VAST provides a structured process and guidance to help a user conduct a vulnerability assessment on their own terms, and interpret their data to better understand vulnerabilities in their system.

Methodology
The underlying framework of VAST is an indicator-based vulnerability assessment, which relies on two key premises. First, that vulnerability is a function of exposure, sensitivity, and adaptive capacity (14). Second, that characteristics of assets—such as their location, condition, or others—can serve as indicators of their exposure, sensitivity, and adaptive capacity (12). VAST is based in Excel and provides guidance to allow a user to derive a vulnerability “score” for a set of assets (which can be defined at any scale) based on these indicators.

VAST steps a user through each step of the process (shown in Figure 4) and provides guidance along the way. The steps entail:

1) Setting the scope of the vulnerability assessment by defining the climate stressors and asset types to be considered. VAST can be used for any climate stressors or asset types, although additional guidance is available for temperature, precipitation, sea level rise, storm surge, and wind as stressors and roadways, bridges, ports, airports, rail, and transit assets as “asset types.”

2) Defining the specific assets to be analyzed. Assets can be defined at any scale. For example roadways could be defined as road segments, roadway categories, or even as “roads” generally (and compared against an entirely different class of assets, for example).

3) Selecting the exposure, sensitivity, and adaptive capacity indicators to be used in the vulnerability assessment. Users enter their own indicators, although the tool provides an “indicator library” with examples of indicators used in previous studies.

4) Collecting data on the indicators for each asset.

5) Defining a scoring approach whereby indicator values are rated and grouped into “bins” (e.g., on a scale of 1-4) and each indicator is assigned a weight as part of the overall vulnerability score.

6) Reviewing the vulnerability results and refining the indicators and scoring approaches as needed.
VAST is designed to be highly flexible and user-driven, and the user provides inputs at every step of the way. As outlined above, users must input: specific assets to analyze, indicators to use (drawing from the indicator library or expert judgment), data on climate stressors and assets for each indicator, scoring “bins” to convert data on each indicator into scores, and weights for each indicator.

To assist users with these decisions, the tool provides guidance. For example, the tool contains an “Indicator Library” with possible indicators, rationale for using each indicator, possible data sources for each indicator, and a possible scoring approach for each indicator. An excerpt of the sensitivity indicator library is shown in Table 3, showing potential indicators for roadway sensitivity to high temperatures. Users can choose to use indicators from the Indicator Library as-is, modify them, or enter their own.

**TABLE 3 Excerpt from VAST Indicator Library – Indicators of Roads Sensitivity to High Temperatures**

<table>
<thead>
<tr>
<th>Indicator</th>
<th>Description and Rationale</th>
<th>Potential Data Source(s)</th>
<th>Example Scoring Approach</th>
</tr>
</thead>
</table>
| Past Experience | Road segments that already experience rutting or other issues related to heat may experience worsening problems as the temperature increases. | • Interviews/surveys with operations and maintenance (O&M) staff | Yes (damaged in past) = 4
<p>|                 |                                                                                         | No = 1                                       |                                               |</p>
<table>
<thead>
<tr>
<th>Indicator</th>
<th>Description and Rationale</th>
<th>Potential Data Source(s)</th>
<th>Example Scoring Approach</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Temperature</strong></td>
<td></td>
<td>• Maintenance or repair records</td>
<td>0-3,000 Truck ADT = 1</td>
</tr>
<tr>
<td><strong>Truck Traffic</strong></td>
<td>Pavement experience greater stress from heavy vehicle traffic. Roads with higher volumes of truck traffic may be more likely to experience rutting, shoving, or other compromised integrity under extreme temperature conditions.</td>
<td>• Emergency response records</td>
<td>3,000-6,000 = 2</td>
</tr>
<tr>
<td><strong>Temperature Threshold in Pavement Binder</strong></td>
<td>Pavement binders are designed to withstand specific temperature thresholds. Asphalt may experience rutting if pavement temperatures exceed the pavement binder thresholds.</td>
<td>• Asset management system</td>
<td>6,000-9,000 = 3</td>
</tr>
<tr>
<td><strong>Condition of Concrete Pavement Joints</strong></td>
<td>For concrete assets only. Concrete is most sensitive to high temperatures around joints, where concrete can heave if temperatures are too hot. In jointed, plain concrete pavement, the traverse contraction joints allow for load transfer without damage to the pavement, as long as the joints are functioning properly. Therefore, the condition of joints is an indicator of how likely concrete assets are to be damaged during high temperatures.</td>
<td>• Engineers within user’s organization</td>
<td>9,000+ = 4*</td>
</tr>
<tr>
<td><strong>Presence of Bus Routes</strong></td>
<td>Similar to the “Truck Traffic” indicator, pavement experiences greater stress from heavy vehicle traffic. Roadways with high bus traffic, truck and bus stopping areas, and truck and bus stop-and-go areas may therefore be more sensitive to temperature-related damage.</td>
<td>• Relevant transit organization(s)</td>
<td>*Bins based on range of truck traffic across assets studied in Mobile, AL</td>
</tr>
<tr>
<td><strong>Use of Polymer Modified Binders</strong></td>
<td>Polymer modified binders are often recommended for areas where extra performance and durability are needed. If polymer modified binders are used on a road segment, therefore, it may be less sensitive to damage from high temperatures.</td>
<td>• MPOs</td>
<td>Projected temperatures exceed threshold = 4</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Institutional knowledge</td>
<td>Projected temperatures do not exceed threshold = 1</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• GIS map of bus routes</td>
<td>Not available</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Engineers within user’s organization</td>
<td>Not available</td>
</tr>
</tbody>
</table>

1 Similarly, the tool provides a starting point, but users can revise the scoring approach for each indicator and the weights assigned to each indicator (Figure 5). Users can use a variety of sources to inform these decisions, such as expert judgment, stakeholder input, or established thresholds. Ultimately, VAST is designed to be a transparent tool that helps the users decide what factors are most important and then systematically apply those factors to the data collected.
FIGURE 5 Screenshots from VAST showing how users can adjust (in the yellow cells) the scoring approach used for each indicator and the weight assigned to each indicator.

Outputs
Once the user completes the process, VAST uses a series of weighted averages (with user-defined weights) to output a table with vulnerability scores for each asset and climate stressor combination (see Figure 6). The tool also provides scores for each vulnerability component—exposure, sensitivity, and adaptive capacity—and “damage,” which is a function of exposure and sensitivity alone. Separating Damage from Adaptive Capacity can provide a more nuanced view of vulnerability and can help enable a deeper understanding of what drives vulnerability results.
Users are free to interpret this data and use these scores to screen for vulnerabilities or identify areas for future analysis. Users are encouraged to use the tool to adjust different assumptions (e.g., indicators used, indicator weights, scoring approaches) to perform real-time sensitivity analyses to see how these assumptions affect results. This exercise of changing the number and weightings of indicators can help identify whether certain indicators are having an inappropriately large effect on the vulnerability results. Involving key infrastructure managers, engineers, and local decision-makers in this process can help ensure the results are well-vetted and actionable.

VAST also generates a results Dashboard, where users can view a summary of asset vulnerability categorized as High, Moderate, Low (as shown in Figure 7); a list of the most vulnerable assets to each stressor (ranked by vulnerability score); and a scatterplot of all assets’ “Damage” versus Adaptive Capacity scores. This Dashboard provides initial analysis and interpretation of the results, though the user is encouraged to pursue a more in-depth analysis.
Applications
VAST can help State DOTs, MPOs, and other transportation agencies—as well as agencies outside the transportation sphere—screen their assets or systems for which specific assets or general areas may be most vulnerable to climate change. This process can help identify areas for more detailed analysis or priority areas to apply strategies to increase resilience.

Areas for Future Research and Development
Additional research and development is necessary into the indicators approach to vulnerability assessment (12). In particular, additional research may be needed to test and validate indicators – the current approach relies on VAST users to apply expert judgment or independent analysis to decide which indicators to apply and how. Indicators will always apply differently in different locations and situations, but there may be value in further analysis to identify whether certain indicators are more effective predictors of vulnerability than others.

Further, the indicator library currently contains indicators for high temperatures, heavy precipitation, sea level rise, storm surge, and wind impacts to roads, bridges, ports, airports, transit facilities, and bus routes. This library could be expanded in the future to include additional stressors—such as changes to freeze/thaw cycles, winter storms, wildfires, drought, or dust storms—and additional transportation asset types.

CONCLUSION
The CMIP Climate Data Processing Tool and Vulnerability Assessment Scoring Tool are two products to come out of the U.S. DOT Gulf Coast Study, Phase 2. They are targeted toward State DOTs and MPOs seeking to reduce their vulnerabilities to climate change. These tools address two barriers that State DOTs and MPOs have faced in this task—accessing and processing climate change projections into practical information, and structuring a vulnerability assessment in an efficient, transparent way. State DOTs and MPOs are already using these tools to begin to reduce their risks. As more agencies use the tools, the transportation community can continue advance the state of the practice in adapting transportation systems to climate change and extreme weather event stressors.

ACKNOWLEDGEMENT
The Gulf Coast Study, Phase 2 was funded by the U.S. Department of Transportation and led by ICF International.
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