## Heavy Vehicle Load Simulator for Bridge Deck Testing Application:

## Volume I

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Submitted by

Patrick Szary, Ph.D\* Associate Director, Principal Investigator Franklin Moon, Ph. D.\* Professor

Andrés M. Roda, P.E.\* Research Manager Gordana Herning, Ph.D, P.E.\* Project Engineer II

David Timian, P.E.\*\* Senior Vice President A&G Sector Manager

\*Center for Advanced Infrastructure and Transportation (CAIT) Rutgers, the State University of New Jersey 100 Brett Road Piscataway, NJ 08854

\*\*Applied Research Associates (ARA) Vertek Division 250 Beanville Rd. Randolph, VT 05060



Kimbrali Davis NJDOT Project Manager New Jersey Department of Transportation 1035 Parkway Ave. Trenton, NJ 08625

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<sup>16. Abstract</sup> Given the importance of overcoming the challenges associated with aging and deteriorating bridges, and the need for a full scale proving ground for evaluation of new and advanced materials and devices, CAIT has procured a full-scale load testing equipment. The Heavy Vehicle Load Simulator for Bridge Deck Testing Application is a one-of-a-kind testing equipment that will evaluate full scale bridge elements and bridge decks in an accelerated manner. CAIT collaborated with Applied Research Associates (ARA) to prepare, design and fabricate the Heavy Vehicle Load Simulator. The equipment will evaluate the samples by applying realistic traffic and environmental loading conditions in a greatly compressed timeframe, simulating 15 years of deterioration processes on full-scale bridges. Since deterioration processes operate over long durations and at a glacial time-scale, time compression is highly desirable. The innovative manners, implemented in this laboratory, to accelerate deterioration processes without distorting them will provide bridge owners with critical information in the near-term. The equipment is a large complex system enclosing a 125' long by 75' wide footprint and standing 13'-6" tall. The equipment that weathers the test sample, simulating seasonal temperature fluctuations (09E to 10.04E) and applying deiger over part ever protect or wing the critical winter monther). The				
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#### **EXECUTIVE SUMMARY**

Given the importance of overcoming the challenges associated with aging and deteriorating bridges, and the need for a full scale proving ground for evaluation of new and advanced materials and devices, the Rutgers Center for Advanced Infrastructure and Transportation (CAIT) has procured a full-scale load testing equipment. The Heavy Vehicle Load Simulator for Bridge Deck Testing Application Laboratory is a one-of-akind testing equipment that will evaluate full scale bridge elements and bridge decks in an accelerated manner. CAIT collaborated with Applied Research Associates (ARA) to prepare, design and fabricate the Heavy Vehicle Load Simulator. The equipment will evaluate the samples by applying realistic traffic and environmental loading conditions in a greatly compressed timeframe, simulating 15 years of deterioration in 6 months (30 fold). This equipment, for the first time, will allow the scientific study of deterioration processes on full-scale bridges. Since deterioration processes operate over long durations and at a glacial time-scale, time compression is highly desirable. The innovative manners, implemented in this laboratory, to accelerate deterioration processes without distorting them will provide bridge owners with critical information in the near-term.

The equipment is a large complex system enclosing a 125' long by 75' wide footprint and standing 13'-6" tall. The equipment consists of a load chassis applying a 60,000lb load in an enclosed environmental chamber that weathers the test sample, simulating seasonal temperature fluctuations (0°F to 104°F) and applying deicers (as per current practice during the simulated winter months). The physical and environmental loading on the test specimens will simulate actual stress and impact levels exerted by truck traffic on bridge decks and superstructure elements at a greatly accelerated pace.

#### BACKGROUND

Long-term bridge performance is currently not well understood, and in practice engineers are forced to rely heavily on expert opinion, heuristics, and generalizations. To fully understand the deterioration process for bridges, and thus develop reliable performance models and early-detection and intervention technologies, the fundamental mechanisms and root causes of deterioration need to be clearly identified.

First and foremost it is important to recognize that the performance and deterioration of bridges is a complex phenomenon, which involves the interaction of many different influences. Formation of cracks in concrete and areas with shallow cover expedites exposure of rebar to chloride ions in salts, which will break down a protective passive film on the rebar surface and initiate corrosion. During elevated temperatures in the summer, penetrated salts, heat, rain, and high humidity further increase the rate of corrosion. Rust on the corroded rebar expands and creates additional cracks that allow water and salts to penetrate deeper into the concrete. During the next winter cycle, trapped water freezes and exacerbates the problem with newly added deicing salts. In parallel with these environmental and winter maintenance inputs, truck traffic on bridges result in deflections and vibration, which create stresses and distortions that may initiate new cracks or open existing ones. The stress exerted by traveling vehicles, particularly heavy trucks, accelerates deterioration by pulling delaminated concrete from the deck and creating potholes or spalling.

To reliably study these complex processes it is necessary to identify a set of parameters that describe the primary drivers of bridge deterioration, and then to vary these parameters in a controlled sense while observing performance/deterioration over time. In this manner, the causal relationships between external inputs (e.g. repetitive live loads, temperature cycles, freeze-thaw, applications of deicing chemicals, etc.), bridge attributes (e.g. superstructure flexibility, cover thickness, rebar coating, girder spacing, etc.), and various performances (associated with durability, serviceability, strength, etc.) can be discerned. Further, since deterioration processes operate over long durations and at glacial time-scales, time compression is highly desirable. That is, innovative means to accelerate deterioration processes (without distorting them) are needed in order to provide bridge owners with critical information on long-term performance in the near-term.

Bridge deterioration begins immediately after construction, and poor construction techniques may exacerbate deterioration. While bridge deterioration is critical to all elements of a bridge, decks in particular, are especially vulnerable. Exposure to the elements and physical loading cycles constantly barrage the bridge deck causing internal cracking, delaminations, surface cracking and eventual failure of the deck. In

focusing on the basic components of the process, bridge deck deterioration can be classified into three main categories<sup>1</sup>:

Chemical deterioration	Physical deterioration	<b>Biological deterioration</b>
- corrosion	- creep	- accumulation of dirt
- carbonation	- fatigue	and rubbish
- alkali-silica reaction	- influence of high	- living organisms
- crystallization	temperature	activity
- leaching	- modification of	
- oil and fat influence	founding conditions	
- salt and acid actions	- overloading	
	- shrinkage	
	- water penetration	

Table 1 – Overview of Degradation Mechanisms (Bien et al.,  $2007)^2$ 

Chemical attacks on bridge decks are particularly damaging. Whether in cold-weather climates or in coastal regions, salts and dissolved salts are the principal chemical deterioration process. When dissolved in water, sodium chloride forms a highly corrosive solution of sodium ions and chloride ions. The very mobile chloride ions penetrate through the concrete pores and where they reach the reinforcing steel and attack the thin passive layer of Ferric Oxide (Fe<sub>2</sub>O<sub>3</sub>) formed on the surface of reinforcing steel during the initial stages of concrete setting. This protective layer is undermined when chloride concentrations attack the Ferric Hydroxide (Fe(OH)<sub>3</sub>) film. The process continually enriches the oxygen levels in a saturated bridge deck. The reinforcing steel

<sup>&</sup>lt;sup>1</sup> Gucunski, N., Romero, F., Kruschwitz, S., Feldmann, R., Parvardeh, H., Comprehensive Bridge Deck Deterioration Mapping of Nine Bridges by Ground Penetrating Radar and Impact Echo, (2011)

<sup>&</sup>lt;sup>2</sup> Bien, J., Elfgren, L. and J. Olofsson (Eds.), *Sustainable Bridges – Assessment for Future Traffic Demands and Longer Lives*, (TIP3-CT-2003-001653) within the 6th Framework Programme of EU, ISBN 978-7125-161-0, Wroclaw, Poland (2007).

gets pitted and can even disintegrate completely. The chloride ions are not consumed during this reaction, but remain fully effective afterwards<sup>3</sup>.

The two most common steel corrosion processes are the chloride induced pitting corrosion and carbonation. The rate of corrosion is dependent on numerous factors including the composition of the metal as well as humidity, temperature, water pH, and exposure to pollution and salt. Wet and dry cycles accelerate the corrosion process. Studies have shown that the corrosion rate is the highest during the spring season and lowest during the winter. These rates can vary by a factor of about four or five times during the year<sup>4</sup>.

The combination of chemical, physical and biological attacks creates a complex deterioration phenomenon that reduces the design-life of our infrastructure. Natural deterioration processes progress slowly over many years, the ability to significantly accelerate the cumulative advance of realistic deterioration of bridge superstructures, decks, and pavement systems is highly desirable. In order to fully understand the deterioration process and thus develop reliable performance models and early-detection and intervention technologies—the fundamental mechanisms and root causes of deterioration need to be clearly identified. To reliably accomplish this it is necessary to: 1) identify potentially influential parameters that contribute to deterioration and 2) vary these parameters in controlled circumstances and observe performance/deterioration over time. In this manner, the causal relationships among parameters (freeze-thaw, temperature cycles, repetitive live-load actions, applications of deicing chemicals, materials, including coating systems, etc.) can be discerned.

Bridge deck repair and/or replacement accounts for over 80 percent of federal and state resources spent on bridge maintenance. While most current bridges are designed for a 75-year service life, bridge *decks* rarely last more than 25 years. Typically, even in the case of the most poorly performing deck, it is 10 to 20 years before there are visible signs of deterioration. Deterioration starts much earlier but cannot be observed without the use of specialized equipment. This is especially true in the case of rebar corrosion, which is identified as one of the main culprits in deck deterioration. How can we understand and find solutions for bridge decks without having to observe the process over a decade or more? The Federal Highway Administration (FHWA) Long-Term

<sup>&</sup>lt;sup>3</sup> Gucunski, N., Romero, F., Kruschwitz, S., Feldmann, R., Parvardeh, H., *Comprehensive Bridge Deck Deterioration Mapping of Nine Bridges by Ground Penetrating Radar and Impact Echo*, (2011)

<sup>&</sup>lt;sup>4</sup> Smith, J. L. and Virmani, Y. P., *Performance of Epoxy Coated Rebars in Bridge Deck*, Report FHWA-RD-96-092, Federal Highway Administration, Washington D.C., USA, (1996).

Bridge Performance (LTBP) program, also led by Rutgers' CAIT, is capable of addressing these challenges given its 20-year duration, however, it cannot do so in the short term.

There are many competing causes for bridge deterioration including environmental (freeze/thaw damage, water containing corrosive salts), mechanical (concrete cracking, fatigue, abrasion), and electrochemical (deicing chemicals, steel corrosion, and certain failures of protective coatings). The Heavy Vehicle Load Simulator is capable of simulating long-term environmental and physical stresses on bridges in an extremely condensed timeframe.

Much of the highway system's segments under-perform and structurally fail far earlier than their intended design life. Traffic volume increases have far outpaced highway construction, particularly in major metropolitan areas. The number of miles driven in the United States jumped more than 41 percent from 1990 to 2007—from 2.1 trillion miles in 1990 to 3 trillion in 2007 (*Transportation Statistics Annual Report: 2007*). In some parts of the country, dramatic population growth has occurred without adequate increase in roadway capacity, placing enormous pressure on transportation infrastructure that, in many cases, was built more 50 years ago. Investment strategies for a steadily aging and deteriorating system are further complicated by higher user demand, budget shortfalls, and squeezed human resources. Effective management strategies that include cost-effective investments are more important now than ever. Efficient management requires performance measures and practical tools to guide decision making.

Perhaps the most critical barrier to safe, sustainable operation and maintenance is our lack of understanding regarding the distinct mechanisms that cause deterioration and poor performance and how those factors influence one another. States currently have conflicting policies related to, for example, superstructure design, choice of deck reinforcement and detailing, etc., that are based on anecdotal experiences and traditions. Even states subjected to similar climates and hazards have vastly different policies related to bridge design, maintenance, and repair. The lack of shared methods and practices is evidence of serious unresolved issues and lack of consensus on how to achieve long-term bridge and highway infrastructure performance. Gaining and *sharing* this knowledge is a critical first step toward developing a sustainable highway system. Within the context of such a clearly evident national need, the Heavy Vehicle Load Simulator will prove its value many times over.

#### **OBJECTIVES**

In order to fully understand the deterioration process for bridge decks, and thus develop reliable performance models and early-detection and intervention technologies, the fundamental mechanisms and root causes of deterioration need to be clearly identified.

To reliably accomplish this it is necessary to (1) identify the potentially influential parameters that contribute to bridge deterioration and (2) vary these parameters in a controlled sense and observe performance/deterioration over time. In this manner, the causal relationships between parameters (such as, temperature cycles, freeze-thaw, applications of deicing chemicals, bridge materials, coating systems, repetitive live load actions, etc.) can be discerned. Further, since deterioration processes operate over long durations and at a glacial time-scale, time compression is highly desirable. That is, innovative manners to accelerate deterioration processes have to be found without distorting them, in order to provide bridge owners with critical information in the near-term.

Given the importance of overcoming the challenges associated with aging and deteriorating bridges, and the need for a full scale proving ground for evaluation of new and advanced materials and devices, acquisition of a full-scale load testing instrument that will be housed at Rutgers University is proposed. This instrument, for the first time, will allow the scientific study of deterioration processes on full-scale bridges. In general, three lines of inquiry are urgently needed with the proposed instrument.

- The first involves the development of reliable predictive models for the remaining life of primary bridge components, most specifically bridge decks. By developing reliable means to forecast and estimate deck performance and safety through the proposed instrument, owners would be in a far more informed position to deploy maintenance and replacement activities as they continue to deal with difficult trade-offs and dwindling financial resources.
- 2. The second line of inquiry is related to the evaluation of numerous technologies, materials, and components, which are being developed to enhance bridge durability and performance. Through the proposed instrument, realistic and reliable estimates of the effectiveness of these new developments can be obtained in a timely manner. This will not only directly aid owners in decision-making, but will also help developers refine their products in a timely manner.
- 3. The third line of inquiry is related to validating new technologies that are being developed for augmenting bridge inspections. The proposed instrument will enable validating new inspection technology by maintaining full-scale superstructures with well-documented and realistic deterioration, defects and damage that are common in various types of bridges.

## INTRODUCTION: CURRENT STATE-OF-PRACTICE AND OPPORTUNITIES FOR INNOVATION

The subsections below provide brief descriptions of a set of both primary and secondary knowledge gaps that currently challenge the effective management and preservative of bridge assets within the U.S. Although this list is not intended to be comprehensive, the items listed were selected since based on the interaction with several states through the LTBP Program.

## Primary Areas of Influence on State of Practice

- Moving Ahead for Progress (MAP-21) Act and subsequent legislation is requiring bridge owners to forecast bridge deterioration as a means of informing infrastructure investment. To adequately perform this task, bridge owners require tools that quantifiably predict deterioration of bridge elements. Current research provides limited spatial and/or temporal resolution and has yet to produce an effective, mechanistic-based approach to accurately forecasting performance with time. This facility will allow researchers to discover deterioration mechanisms that contribute to bridge performance, and as a result will help researchers develop quantifiable methods of forecasting deterioration to inform investment.
- 2. Decision-makers are considering legislation to increase the limits of allowable truck weights in an effort to boost economic growth. Bridge and asset owners are increasingly concerned about the effects of higher axle weights as they currently have limited quantitative data that illustrates the influence on performance. This facility provides an immediate opportunity to inform bridge owners on the effects of higher axle weights.
- 3. There is currently much variation in the deck rebar policies across the U.S. (even for states within the same environmental regions). For example, some states require epoxy-coated rebar be used for both top and bottom mats, while others require epoxy-coated rebar only for top mats. Further, several states have started to require uncoated bars made from corrosion-resistant steels (e.g. stainless steel, MMFX2). Identifying time to incipient corrosion, and subsequent performance post corrosion is critical to the selection of rebar type/coating. Ultimately providing bridge designers with a validated life-cycle performance model of rebar types will improve the selection based on the location of the bridge on particular corridors (local, rural, urban, arterial, etc). Thus, full-scale testing that combines both mechanical and environmental loading will provide observational, empirical and quantifiable evidence of rebar performance by type and coating.

#### Secondary Areas of Influence on State of Practice

- 1. Shear studs sprout debates among designers, materials engineers and researchers. There is clear positive influence on bridge efficiency related to live load capacity, but also potentially negative influences related to deck rebar cage congestion and their role as potential delamination initiators. The Heavy Vehicle Load Simulator provides a unique opportunity to observe, measure and evaluate shear stud performance within the specimen; and provide findings to the bridge community that may spur innovative solutions to minimize early-age localized deterioration in the immediate surrounding of shear studs.
- Among limit states considered in bridge design, temperature/thermal stresses
  receive minimal attention. Researchers have developed hypotheses concerning
  early age cracking of reinforced concrete decks over structural steel
  superstructures, which identify thermal stressors as potential culprits.
  Determining whether threshold tensile stresses are exceeded during freezing
  cycles will provide great insight to the design community as it considers thermal
  loading from the dissimilar materials.
- 3. Similar to shear stud placement and early age cracking due to thermal stresses, understanding composite action as it relates to the concrete/structural steel interface is critical. Determining long-term performance of composite action on full-scale was previously onerous. The facility offers an opportunity to evaluate the influence of deck deterioration on composite action. In addition and similar fashion, the facility can offer opportunities to study transverse load distribution of live load force effects.
- 4. During the design of bridges many states permit the super-imposed dead loads (SDL) to be assumed to be smeared equally across all girders. Although this grossly under-estimates the actual forces imposed by SDLs to exterior girders, the ability of the bridge to redistribute such forces through shake-down is commonly cited as a justification. The Heavy Vehicle Load Simulator offers a unique opportunity to examine this shake-down phenomenon and also to evaluate the validity and/or influences of assuming SDLs to be uniformly distributed.

The envisioned research concept using the procured equipment is to investigate three fundamental objectives:

• Develop a *standard* to define bridge performance: Bridge performance relates to overall highway system performance, which is often expressed in terms of safety, efficiency, environmental impacts, cost, and organizational effectiveness. The principal challenge in establishing standards for bridge performance is developing quantitative, measurable indices that strongly correlate to the desired global performance of the entire system. The Heavy Vehicle Load Simulator will, for the first time, make it possible

for critical parameters and inputs that affect bridge performance to be controlled under realistic (but accelerated) operating conditions. This will enable scientific study to clearly establish in the near term the influences and compounding effects on long-term bridge performance.

• Identify critical parameters and how they impact bridge lifecycle performance:

Building on the definition of a bridge performance standard, the root causes and mechanisms of deterioration and damage that lead to undesirable performance will be identified and understood. Developing a facility for accelerated and climate-controlled load testing would be the only practical way to achieve timely and scientific understanding and modeling of the root causes of deterioration, how deterioration impacts performance over time, and how one may effectively mitigate these impacts through proper operational and maintenance management.

• Evaluate and develop advanced materials: The Heavy Vehicle Load Simulator also will enable evaluation, testing, and development of efficient, longer-lasting roadways of the future. It is envisioned that the Heavy Vehicle Load Simulator will be complemented and become part of research on a wide range of materials, material testing systems and procedures, construction quality control methods, and asset management areas that support the national strategy of maintaining and repairing our aging highway system and will therefore promote economic growth as it relates to the efficient movement of people and goods.

#### **Historic Context**

## 2010 National Institute for Standards and Testing (NIST) Competition

In 2010 CAIT submitted a proposal for a NIST Construction grant (Funding Opportunity 2010-NIST-CONSTRUCTION-01). At the time, the proposed Heavy Vehicle Load Simulator (at the time was housed in the Accelerated Infrastructure Testing Facility or AITF) was envisioned as a mechanical live load simulator equipment coupled with a 25,792sf climate-controlled testing building, a 30,000sf Data Control/Evaluation and Advanced Materials Testing Laboratory, a Pavement Profiler Certification Test Track, and a Pavement Testing Area. As depicted in the 2010 grant:

#### Project at a glance (Taken directly from the 2010 NIST Construction Grant proposal)

Unique facility where the most critical aspects of the highway transportation system (bridge superstructures, decks, and pavement systems) will be constructed and evaluated applying realistic, traffic and environmental loading conditions in a greatly compressed timeframe.



- 25,792sf variable-environment testing building (16,120sf and 9,672sf test bays)
- 30,000sf Data Control/Evaluation and Advanced Materials Testing laboratory
- Custom-designed Heavy Vehicle Load Simulator
- 1,000 ft long Pavement Profiler Certification Test Track and Pavement Testing Area



Figure 1. Schematic illustrating early concept of the envisioned test bed of the facility

According to the American Association for State Highway Officials – Load and Resistance Factor Design (AASHTO-LRFD) Bridge Design Specification (section C3.6.1.2) the estimated maximum daily truck traffic per lane on an interstate bridge is 4,000 trucks. At the time, the equipment was described, and shown in Figure 1, as an automatic, accelerated pavement loading device that would apply approximately 5,000 passes of the load carriage during a 24-hour period along a 160-foot test section centerline. The load carriage would accommodate mounting of two standard truck axles coupled with super-single or dual truck tires. The system concept was based on accelerated pavement testing using machines that originated in Gautrans South Africa in the 1960s. As a comparison, Dynatest models currently in service include: Mark IV, owned by Florida Department of Transportation (FLDOT), U.S. Army Corps Frost Effects Research Facility (FERF), Mark V (Bigfoot), owned by U.S. Army Corps, and Mark VI, Owned by the University of California Pavement Research Center (UC-PRC).



Figure 2. Dynatest MARK VI model (http://www.dynatest.com/equipment/accelerated-pavement-testing/hvs.aspx)

CAIT correctly anticipated that the NIST competition would be highly competitive, with over 100 applicants nationwide. At the end of the competition, CAIT was not selected for the grant. Thus, CAIT requested a No-Cost Extension (NCE) to continue its concept

development and refine the design to better compete in the 2011 NIST Construction Grant.

## 2011 NIST Competition

In 2011 CAIT submitted a second proposal for NIST Construction grant (Funding Opportunity 2011-NIST-CONSTRUCTION-01). The second proposal incorporated significant changes from the 2010 proposal. As depicted in the grant:

# Project at a glance (Taken directly from the 2011 NIST Construction Grant proposal)

The proposed Accelerated Infrastructure Testing Facility (AITF) is envisioned as a national hub for research, development, and standardization of technologies and materials to support infrastructure systems engineering, operations, and management. The AITF will be a unique facility where the most critical aspects of the highway transportation system (bridge super-structures, decks, and pavement systems) will be constructed and evaluated by applying realistic traffic and environmental loading conditions in a greatly compressed timeframe.



- · 24,560sf testing building with a variable-environment chamber
- 30,000sf Data Control/Evaluation and Advanced Materials Testing Laboratory
- Custom-designed Magnetically Propelled Loading System (MPLS) as the Heavy Vehicle Load Simulator (Under this project)

The 2011 concept for the proposed Heavy Vehicle Load Simulator consisted of a magnetically-propelled loading system conceptualized by CAIT and MagneMotion, a Rockwell Automation Company. The proposed mechanical live load simulator equipment consisted of a load trolley propelled by an innovative industrial electromagnetic system. The trolley would comprise two axles that carrying 32 kips of live load per axle (64 kips per two-axle trolley), equivalent to 1-1/2 times the legal limit defined by FHWA (*USDOT Comprehensive Truck Weight Study: 2000*). During repeated environmental loading cycles, the proposed Heavy Vehicle Live Load Simulator would have applied more than 6,900 truck passes per day at a loading level that would exceed the legal truck weight limit.



## Figure 3. Concept drawing of Magnetically Propelled Loading System

Using an array of electromagnets to power the Heavy Vehicle Load Simulator provided several advantages: significant thrust (0 to 20 mph in less than 3 seconds); precise, computerized controls; virtually noise-free operation; energy efficiency (in that it would not require 24/7 operation of a diesel engine like field loading would); and clean operation without mechanical, contact-driven, or hydraulic systems. This system also had the potential to control multiple trolleys simultaneously.

The load trolley would accelerate at 10.5 f/s<sup>2</sup> along a permanent concrete abutment leading up to the test specimens. The propulsion system would be capable of powering the trolley to reach 20 mph in 2.8 seconds, then maintain a constant speed of 20 mph along a 200-ft test area. The test area would hold four 50-ft superstructures OR two 100-ft superstructures. The load trolley would travel over the specimens, then decelerate on a second permanent concrete abutment on the far side of the test area, stop, and restart the process in reverse. The 2011 proposed version of Heavy Vehicle Load Simulator was designed to make approximately 6,900 one-way trips "cycles" at 20 mph during a 24-hour period.

The research team collaborated with MagneMotion to conceptualize the thrust of the electromagnetic drive system, the axle configurations, and trolley loading to optimize the

acceleration/braking length of the permanent concrete abutments. The minimum design criteria was based on accelerating the two-axle load trolley to 20 mph, maintaining constant velocity for 200ft, and decelerating to a stop. Based on engineering calculations, the research team selected 60-ft ramps as the optimum acceleration and deceleration zones. Analysis showed that longer ramps would be impractical, especially in relation to the length of the environmental chamber. Shorter ramps would not allow enough room for the trolley to reach the speed required to accomplish the desired number of passes per day and therefore adequately accelerate loading deterioration of the specimens.

The concept was envisioned to achieve the testing goals as well as accommodate several other load scenarios for future testing programs, including but not limited to the following combinations: two-axle 64-kip at any speed less than 20 mph; three-axle 96-kip at any speed less than 14 mph; two-axle 80-kip at any speed less than 16 mph; three-axle 120-kip at any speed less than 12 mph; and two-load-trolley scenario with two (2) two-axle 64-kip (total load 128 kips) at any speed less than 10 mph. The flexibly of having multiple variables—loads, speed, number of axles, and even axle spacing—represented an extremely robust live-load protocol.

The 2011 grant proposal submission incorporated the proposed environmental loading protocol developed by Dr. Seung-Kyoung (SK) Lee:

**Step 1:** An ambient exposure cycle starts. Wheel loading will induce hairline cracks in the test concrete. Ambient exposure 25°C (77°F) and 60% Relative Humidity (RH) for 2 days

**Step 2:** Freeze exposure cycle starts. Periodic deicer sprays will apply chloride ions on the concrete surface, which will then be absorbed through concrete surface, especially through cracks. Repeated exposures to freezing cycles will cause surface scaling. Freezing exposure with periodic deicer spray -18°C (0°F) and 40% RH for 5 days

**Step 3:** Thawing exposure cycle will follow. This period will provide an opportunity for freezing thermal loading to be released, leaving new cracks open for additional liquid and chemicals to enter the structural element. "Low" ambient-thawing exposure 20°C (68°F) and 50% RH for 2 days

**Step 4:** Once thaw exposure cycle is complete, another cycle of extreme thermal loading will follow. A hot and humid exposure cycle representing a typical summer will increase the rate of corrosion significantly due to elevated electrochemical activities. In addition, corrosion of rebar in concrete will increase as concrete resistivity decreases by absorbing humid ambient air. The cycle will conclude with hot and humid exposure with constant ultraviolet (UV) rays 40°C (104°F) and 95% RH for 5 days

This conceptual four-step cycle would be repeated until the bridge reached a

predetermined state of deterioration. The method was developed based on FHWA research performed by Dr. Lee.<sup>5</sup>



Figure 4. Concept drawing of environmental chamber

In 2011, within the proposed environmental chamber, it would be possible to apply, measure, and quantify environmental impacts and understand their influence on the phenomenon of infrastructure aging and deterioration. It was proposed that the chamber be constructed to support the thrust/braking forces of the Heavy Vehicle Load Simulator, seal and insulate the conditioned space, and apply thermal loading, desirable RH, and deicing chemical solution (via an automatic spray system) on the test specimens. Heat and UV lamps also would be used to elevate surface temperature and simulate UV-ray exposure. Alternating extreme high and low temperatures would induce substantial thermal stress (expansion and contraction) into the body of concrete decks and other structural members, similar to that which occurs under real-world conditions.

The enormous scale of the proposed test specimens in 2011 required a custom-built chamber. It was postulated that such an environmental chamber would accommodate up to 600,000 lbs of concrete (four deck slabs each 50ft long × 20ft wide OR two deck slabs each 100ft long × 20ft wide) plus the weight of a superstructure up to 200,000 lbs (plate girders, 50-ft or 100-ft lengths). The chamber was designed in collaboration with McLaren Engineering Group as a structure unto itself, which needed to be 350ft long x 46ft wide x 29ft high, as detailed in Figure 5, and capable of conditioning the samples as well as be able to withstand the harsh corrosive environment and its own thermal expansion.

<sup>&</sup>lt;sup>5</sup> SK Lee. Accelerated Testing of Corrosion Resistant Reinforcing Bars. Presentation at FDOT seminar, 2012, website:



## Figure 5. Concept of environmental chamber to house the Heavy Vehicle Load Simulator

Such a chamber would be able to apply environmental temperature and/or humidity levels in any combination, ranging from 0°F to 104°F and 40% RH to 95% RH. Any target temperature and RH would be achieved within a day of changing the settings. The chamber was designed to optimize the environmental loading effects on the specimens, simulating an entire year's worth of seasonal variation in just 14 days. The critical objective was to induce temperature changes at a depth of two inches from the surface, at the location of reinforcing steel.

Through consultation with Dr. Lee, CAIT determined that combining simulated highvolume significantly overweight truck loading with environmental loading cycles in a condensed timeframe would accelerate deterioration of the test bridge specimens. Compared to normal wearing conditions, the Heavy Vehicle Load Simulator would be able to accelerate deterioration at a rate 32 times faster than *in situ*; however, taking into account the complex interactions at play, plus the overweight loading, the rate would likely be even higher.

The 2011 competition was cancelled by NIST, with no consideration for submissions.

## SUMMARY OF THE WORK PERFORMED

## **Final Design and Subcontractor Selection**

As shown in the introduction, the AITF was separate from the Heavy Vehicle Load Simulator. The AITF was envisioned as a construction grant to build buildings to support a number of research initiatives – one of those buildings was intended to house the Heavy Vehicle Load Simulator equipment. Following the cancellation notice received from NIST, CAIT considered alternatives. CAIT first considered renting warehouse space near-campus to house the equipment. This proved impractical due to the following:

- · limited ceiling clearances
- need for customized large open bays without columns to allow space for the equipment
- need for customized very-large doors needed to move large bridge specimens
- reaction flooring or other customized foundation to support the specimen, equipment and mechanical live loading
- · other ancillary needs

CAIT also considered other funding sources to erect housing for the equipment. The team coordinated with Applied Research Associates to develop a preliminary design that would allow for the fabrication of the equipment suitable for the outdoors and delivered to a site suitable for the equipment.

#### **Design Criteria**

The preliminary design specifications for the equipment is depicted in Table 2.

Specification	Bridge Deck Tester
Chassis Style	Bridge style
Test Bed Elevation	Up to 60 inches above floor
Length at Speed (ft)	50 ft
Total Travel (ft)	50 ft plus deceleration travel plus axle spacing
Overall Length (ft)	Under 120 feet
Overall Weight (lb)	120,000 lb*
Carriage Weight (lb)	10,000 *
Max Normal Load (lb) Normal	60,000
Min Normal Load (lb) Normal	10,000
Load Stability (% target)	+/-5%
Load Accuracy (% fso)	+/-5%
Trafficking Speed (mph)	0 to 20
Return Speed (mph)	Same as trafficking speed

 Table 2 - Heavy Vehicle Load Simulator Design Specifications

Primary Drive System	Electric winch	
Axle Size	Two Full 30,000 lb capacity each	
Tires	4 pairs of Dual	
Variable start/stop position	No	
Computer Fault Monitoring	Yes	
Tire Pressure Monitoring	Yes	
Tire Pressure Control	Yes	
Environmental Control	Yes	
Load Method	Pneumatic	
Wander Method	Not Included in Base System, Optional	
Bridge Deck Size Capability	1- 20ft x 50ft x 1ft Bridge (later changed to 28ft	
	width)	
Portability	With Hydraulic lifting Dollies (later changed to rail	
	carts)	
Bi-directional Loading	Yes	
Unidirectional Loading	Not Included	
Electrical Power	3 Phase 480 Volt	

The following subsections provide explanation over various system components:

#### Load Carriage

The load carriage is a standard dimension truck tandem axle dolly equipped with an air suspension. It is designed for the base requirements of 0 to 20 mph variable speed, bidirectional loading. The axles and air suspension are sized to handle up to the 60,000 lb (30 ton) live load requirement. An onboard air compressor supplies pressure for the desired loading. The air suspension maintains and stabilizes the load (similar to truck suspension) as the bridge deteriorates. An electric propulsion system provides power to move the carriage.

The load carriage has two sets of wheels in addition to the trafficking wheels/tires; load wheels and return wheels. During test operations, when load is being applied to the test section, steel wheels mounted on the carriage roll along the steel rails mounted under the main frame. In this case, the force of the loading wheel keeps the steel carriage wheels pushed firmly against the rails. When bridge deck loading is not being applied, the gravity load of the carriage is supported by the return wheels that travel on top of the bottom flanges of the main frame beams. Horizontal guidance of the carriage is provided by cam bearings that are positioned to react against the side of the main frame.

The lateral position of the load carriage is set by locating the Heavy Vehicle Load Simulator for the test load position desired. Figure 6 shows the range of possible locations of the wheel loads on the bridge from far left to far right. The position of the load wheels can be at any location between far left and far right, but can only be changed by re-positioning the equipment.



Figure 6. Range in Position of the Load Carriage

## Environmental Enclosure

The preliminary design of the environmental chamber was proposed as an aboveground enclosure constructed of insulated panels at least four inches thick and would enclose only the bridge structure. The panels on one end would be removable to enable the load carriage to be removed. It was envisioned that the roof of the chamber would be attached to the Heavy Vehicle Load Simulator main beams and be hinged, like wings, such that they could be raised and moved with the equipment during deck replacement. This design is consistent with the curtains used on pavement testing equipment.



## Figure 7. Concept sketch illustrating the roof of the environmental enclosure

## Specimen Design

Given its widespread use in practice, a steel multi-girder with a composite reinforced concrete deck is proposed as the initial specimen. To maximize the usable space within the environmental chamber, the specimen will have a 28 ft. width and a 50 ft. length.

These dimensions will allow for four girders spaced 7 ft. on center with 3 ft. overhangs along each edge. A span-to-depth ratio of L/25 is proposed for the girders, which gives a girder depth of 2 ft. To permit multiple lines of diaphragms, a spacing of 17.3 ft. (which provides two internal diaphragms in addition to those over the supports) is proposed. Given the relatively small girder depth, channel type diaphragms are likely the most realistic option; however, the use of cross frames (perhaps in a chevron configuration) will be considered.

To ensure a realistic design, the girders will be sized as per the AASHTO-LRFD Bridge Design Specifications based on the simplified single-line girder modeling approach and will be designed to be composite (using standard shear stud connectors and spacing) with the reinforced concrete deck. This approach is the most commonly used in practice and will result in the most realistic girder and superstructure stiffness and strength characteristics. To permit the examination of two steel coating systems, it is proposed to have two of the girders be coated with a common paint system and two of the girders be constructed of weathering steel.



Figure 8. Conceptual design of a typical bridge specimen illustrating the proposed live load location and magnitude

## **Brine Application**

A batch brine application system is provided to expose areas of the bridge to the corrosive solution. The brine solution is applied to the top surface of the bridge along its 50 foot length as initiated by the control system. Frequency of application is determined by the researchers and is estimated to be two times per 24 hour period. A separate system stores and mechanically agitates brine to maintain at the desired concentration between 1% and 15% salt solution with the capacity of at least 200 gallons. During

distribution, this brine is mixed with tap water through a mixing valve resulting in a 1% to 2% brine solution being distributed to the bridge.

During the freeze cycles, the distribution pipes will need to be cleared or heated to prevent the brine from freezing. A 1% - 15% brine will freeze at approximately 30°F, and a 15% brine will freeze at approximately 12°F. The lines could be cleared using dry air, however a pipe at 0°F will start to freeze the brine as it is being pumped into the chamber and may ultimately block the system near the end of the two day cold cycle.

The challenges with the brine solution system were addressed via design changes that are documented in the final design section.

## Site Requirements

In order for the equipment to function properly, the University was required to improve the site, including construction of foundations to support both the bridge and separately the Heavy Vehicle Load Simulator. In addition, the University was required to install an underground utility trench to provide the power, water and communications to and from the Heavy Vehicle Load Simulator. Underground was required due to the use of a large crane to move new and old bridge specimens into and out of the environmental chamber. The site and facilities required to assemble and operate the bridge deck tester are summarized in Table 3 and Figure 9. The University provided a site near the existing pavement testing laboratory on Livingston campus.

Item	Requirement	Comment
Length	120 feet	Clear
Width	40 feet	Clear
Height – working	20 feet	Clear above parking area
		adjacent to the test
		machine as well
Power - Line Voltage	480 Volts, 3 phase, 60 Hz	Is 480V available?
Power - Current	900 Amps	
Water	2 GPM	Supply
Surface load capacity	2 TSF (27.8 psi)	Estimate
Site Access	Tractor Trailer capable	See drawing
Site Access	Fork lift capable	Asphalt pavement is
		adequate
Bridge Deck Foundation	To support test decks	Permanent below frost line
Bridge Deck Testing	To support machine	Permanent below frost line
Foundation		
Frost walls	To support sides of	Attached to Bridge Deck
	environmental chamber	Testing Foundation at
		each end; below frost line
Lateral movement rails	To move system across lot	Placed at parking lot grade

 Table 3 - Site Requirements for Heavy Vehicle Load Simulator



Figure 9. Proposed site layout in 2013 showing surface and subsurface items (not included in project)



Figure 10. Site Location

The location was selected based on its many beneficial properties. The site on Livingston Campus is the former Camp Kilmer Military base. In addition to warehouse space, the site is conveniently located near State Route 18, State Route 1, Interstate I-287 and the New Jersey Turnpike. The location is critical for bridge construction, as material transport requires access to the state and interstate highway systems.

## Equipment Final Design

ARA developed a series of preliminary design concepts for review and consideration. The resulting final design was incorporated and comprises the equipment that was procured. The following key changes were enacted to improve the Heavy Vehicle Load Simulator:

- · Change from dolly system to rail carts for lateral movement
- Environmental tub and modular roof truss design
- Revised tub design to accommodate 28-ft bridge specimen

The evolution of the design is presented below as a synopsis of major changes and their results.

## Lateral Movement

The Heavy Vehicle Load Simulator was designed to either ride on a dolly system or rest upon rail foundations. A 2013 concept sketch depicts an early permutation of the equipment concept.



## Figure 11. Preliminary design sketch depicting the Heavy Vehicle Load Simulator

As shown in Figure 11, four (4) movable dollies were envisioned to position the Heavy Vehicle Load Simulator over the specimen. In this design, above-ground foundations would support the specimen, and separate above-ground foundations would support the Heavy Vehicle Load Simulator.

The desire to closely control lateral movement also played a key role in selecting this option. The team considered the long span of the twin box beams, 114-feet measured from beam ends, too far from end to end in order to control movement of the supporting end frames without racking the beam pair. Movement of the independent dolly system would need to be coordinated closely to avoid racking. A more simple approach was to use a pair of rail carts that could be controlled simultaneously and remain aligned on

rails placed using survey-control lines. The resulting system provides the equipment computerized control of movements that minimize lateral and vertical misalignment.



Rail Cart (typ.)

#### Figure 12. Heavy Vehicle Load Simulator design on rails

The final design of the Heavy Vehicle Load Simulator was designed to be moved laterally by rail carts, which would incorporate a lifting mechanism to allow for the equipment to be lifted and lowered to position. Figure 12 illustrates the equipment supported and moved on rail carts.

#### Environmental Tub and Modular Roof Truss Design

ARA produced a draft transient heat analysis to estimate the capacity of the Heating, Ventilating and Air Conditioning (HVAC) system required to heat and cool the proposed environmental chamber. ARA utilized freely available material properties for conduction and radiation heat transfer parameters, and estimated convection coefficients based on turbulent airflow provided by an array of ducts and fans. The analysis simulated the heat flux between objects in the domain, and metered temperature changes based on the heat capacity of those objects. The air conditioning and heating unit was simulated by a constant heat loading to the air inside the insulated chamber. A diagram of the geometric configuration of the analysis is presented in Figure 13.



## Figure 13. Geometric configuration of the environmental analysis

In the analysis, concrete is allowed to conduct heat to steel. Otherwise, heat is transferred via convection and radiation from the materials inside the box to the air and internal walls. The insulated box loses heat to the ambient exterior via conduction through the insulation and natural convection to the exterior. In order to better control temperature demands during testing, the team redesigned the tub to be embedded into the ground. This provided insulation from external high and low temperatures via soil temperatures that vary less widely.

The operational target for cooling the concrete test slab is  $0^{\circ}F$  (-18°C) during the cooling cycle, and heating to  $104^{\circ}F$  ( $40^{\circ}C$ ) in the heating cycle. The cycles should take approximately 24 hours. Presented in Figure 14 are several heating and cooling curves generated by the analysis assuming a 77°F ( $25^{\circ}C$ ) ambient external temperature.



#### Figure 14. Temperature of the concrete slab over time with different capacity HVAC systems delivering heat flux to the air

The redesigned environmental chamber tub comprises two (2) full-height abutments, two (2) frost walls to form the enclosure, and 20-lb rails with concrete foundations. The upper portion of the environmental chamber is the modular roof, as shown in Figure 15,

which is composed of 3 distinct items: the end frame environmental enclosures, the beam mounted insulation, and the roof trusses with the foam mounted to them. These three components form the movable portion of the environmental chamber. The end frame enclosures surround the loading ramps and provide space for the carriage to move off the deck and still be enclosed in the chamber. The beam mounted insulation provides the environmental enclosure between the load ramps and the roof trusses. The roof truss portion of the environmental chamber is designed to allow the Heavy Vehicle Load Simulator to be located at different spots across the bridge deck and still be environmentally contained. Each roof truss section can be separated from the others and then be relocated to the other side of the Heavy Vehicle Load Simulator. The lateral adjustment is provided by the beam mounted insulation that reaches out to cover and interface with the roof trusses.





Figure 15. The Upper Environmental Chamber, Beam Mounted Wings (top) and Roof Trusses (bottom).

The roof trusses move on the rails that are attached to the abutments. The roof trusses have two wheels on each side that move along these rails as shown in Figure 15. The roof trusses are sealed by clamping them together with a cam lock system using a hex wrench as shown in Figure 16.



Figure 16. Roof truss track rollers and truss sealing mechanism

The system is modular, allowing the equipment to move laterally for either load placement on the specimen or for specimen placement, which requires a complete exposure of the environmental chamber. Figure 17 illustrates the position of the Heavy Vehicle Load Simulator laterally moved away from the tub; and roof trusses tucked under the equipment to allow for bridge specimen placement. Figure 19 is a rendering of the installation of a bridge specimen. Although conceptual, it illustrates that bridge specimens may be prefabricated prior to placement, or (not shown) can also be cast-in-place and cured inside the environmental chamber.



Figure 17. Bridge specimen placement



Figure 18. Rendering of bridge specimen installation

Once the bridge specimen is in place, the equipment can be laterally moved over the tub to seal the bridge specimen into the environmental chamber. The equipment can be positioned over the bridge at any desired position to load the bridge specimen. This flexibility is achieved through the design of the roof truss system. Four (4) roof truss modules combine with an externally attached roof truss on the Heavy Vehicle Load Simulator to comprise the environmental chamber roof. Figure 19 depicts the equipment placed off-center over the bridge specimen. In this scenario, three (3) roof truss

modules are located to the left of the equipment and one truss module is placed on the right of the equipment. The equipment rests over two of the modules to seal the tub.



Figure 19. Cross section depicting the Heavy Vehicle Load Simulator positioned over bridge specimen

## Revised tub design to accommodate 28-ft width bridge specimen

As discussed in the 2<sup>nd</sup> quarter 2014 meeting and in response to the Department's comments, the team revised the tub configuration to accommodate a 28-ft width bridge specimen. The basis for this change was to accommodate a bridge section that is more commonly and typical of in-service bridges. The Department suggested 12 to 14 foot girder spacing be considered, resulting in 28-foot bridge specimen width. The larger dimension required changes in the roof and lateral travel accommodation; both incorporated into the final design.

## DESCRIPTION OF THE FABRICATED EQUIPMENT

The following section describes the key elements of the equipment, as fabricated and delivered to CAIT. For a more detailed review and description, see Volume II titled, "Operations Manual & Standard Operating Procedures."

## **Overall Structure**

As shown in Figure 20, the Heavy Vehicle Load Simulator structure consists of two main box beams that run the length of the machine. The box beams are attached together by 7 cross braces and two end frames. A winch end frame houses controls and the winch and a sheave end frame houses the sheave assembly. Both end frames are supported on a leveling frame. Inside of the end frames there are two powered railroad carts that lift and move the machine when needed. In the center of the two box beams the carriage assembly rides on two rails that run the full length on the bottom of the beams.



#### Figure 20. Heavy Vehicle Load Simulator Overall Structure and Main Components

#### Winch and End Frame Assembly

The winch end frame assembly houses most of the drive and control components of the Heavy Vehicle Load Simulator. As shown in Figure 21 and Figure 22, the 400 horsepower winch assembly, the winch controller, the electrical main distribution panel (MDP), the programmable logic controller (PLC, shown in Figure 23), and the rail cart controllers are all housed in this enclosure. The winch provides the force to move the load cart. The winch controller interfaces with the PLC, which in turn is controlled by the control computer in the control room. The winch controller interprets the commands from the PLC and provides the proper current to run the motor. It also directs the excess current generated when the load carriage is stopping to the braking resistors located next to the winch. The MDP is the electrical connection to the transformer that provides power to the Heavy Vehicle Load Simulator. It is wired for 3 phase, 480 volt power. Another transformer in this enclosure provides the 240 and 120 volt power for lights and other uses. The PLC is attached to the sensors located in other portions of the Heavy Vehicle Load Simulator. Based on the instructions coming from the control computer and the sensor output, it provides the command signals to the winch controller to operate the load cart. The rail cart controllers are commanded with a hand held controller attached directly to the controllers via a special connection. The rail carts can lift the whole Heavy Vehicle Load Simulator and move it laterally on the rails to allow access, maintenance or replacement of the bridge deck being tested.



Figure 21. Winch End Frame Assembly Showing Winch, MDP, and Winch Controller.



Figure 22. Assembly Showing PLC and Rail Cart Controllers in Winch End Frame.



Figure 23. Detailed view of the PLC interface

#### Sheave End Frame Assembly

The Sheave End Frame Assembly supports the sheave end of the structure, houses the sheave, and the sheave end rail cart as shown in Figure 24. The sheave assembly itself is comprised of a support frame, a guide beam, a large pneumatic cylinder pressurized with nitrogen and a yolk that holds a large pulley. The winch cable wraps around the pulley and the pressure in the pneumatic cylinder maintains tension on the winch cable attached to both the winch and one end of the load carriage. The sheave guide beam also has two sensors attached on it that provide data to the control system to make sure the sheave does not move to a point where it could not maintain tension on the cable. The sheave provides a means to take up both the dynamic cable movements as the load cart moves, and the static stretch of the cable as it lengthens as it is used.



Figure 24. Sheave End Frame Assembly

## **Rail Carts**

The rail carts as shown in Figure 25 are constructed of structural steel and plate members welded into a heavy duty unit suitable for lifting and moving the Heavy Vehicle Load Simulator. The unit is equipped with a 3/4" flat steel deck plate with removable access covers to allow access to the components beneath the deck. A mechanical screw jack arrangement is powered by a 480 Volt AC SEW-Eurodrive gear-motor providing 6" of vertical lift. A drive axle arrangement consisting of (2) 16" diameter single flange steel wheels, SKF Flange Bearings, C-1045 carbon steel axle and a 480 Volt AC SEW-Eurodrive gear-motor is mounted on the rear of the unit and (2) Idler Wheel Assemblies mounted on the front. Both of the gear-motors are equipped with a spring applied and electrically released motor brake to prevent movement when the power is off.



Figure 25. Rail Cart Assembly

The rail carts are set up as a "master" and "slave" arrangement whereas each car is controlled by a single Allen-Bradley PLC mounted in the winch end frame, as shown in Figure 26, and each car is equipped with a variable speed drive used to control the drive arrangement. Each cart is equipped with an encoder allowing the PLC to synchronize the lift of each endframe. The drive arrangement provides travel speed of 2-10 feet per minute (FPM).



Figure 26. Rail Cart Control System

The "master" car is equipped with a hand held pendant control equipped with a variable speed control, forward/reverse and lift/lower controls as shown in Figure 27.



Figure 27. Rail Cart Handheld Pendent Control

## Leveling Frame and Jacks

The leveling frame, shown in Figure 28, provides a means to make up minor differences in height and slope between the Heavy Vehicle Load Simulator and the test section. The end frame fits over the leveling frame and the leveling jacks adjust for the differences in height from end to end or side to side. Shear clamps are also provided to allow any impact or side loads to be transferred into the concrete structure from both the end frame and the leveling frame. The multiple views below show how the frames and clamps fit together.





#### Winch Assembly

The winch assembly is an electrically powered cable drum used to propel the carriage assembly back and forth. It has a 400 HP 480 Volt 3 phase drive motor with encoder feedback and a gear reducer. The drum rotation speed is reduced by powering the motor in the opposite direction. While the drum is still spinning in the original direction the excess current is redirected through a bank of resistors to dissipate the excess energy. The main components of the winch assembly are shown in Figure 29.



Figure 29. Winch Assembly

#### **Tension Cylinder and Sheave Assembly**

The Tension Cylinder and Sheave are located at the opposite end from the winch on the sheave end frame. The Tension Cylinder is pneumatically operated and provides tension to the wire rope. Typical pressure is 80 psi and applies about 12,000 lbs. of pull on the sheave wheel. Two limit switches detect the extents of the cylinder position. These switches are connected to the E-stop circuit and will shut the Heavy Vehicle Load Simulator control system off when the cable stretches enough to reach the limit of the cylinder stroke. It will also shut down if the cable goes slack and the Sheave fully retracts. The details of the Sheave assembly are shown in Figure 30.



Figure 30. Sheave Assembly

## Carriage Assembly

The carriage assembly provides the tire loading to the bridge deck test surface. Figure 31 is a side view of the complete carriage assembly. It is comprised of two parts, the upper and lower sections. The upper section guides the carriage and also provides a load path to react against the load applied to the bridge deck. The lower carriage has the truck wheels and tires and applies the load to the bridge deck. In between the upper and lower portions of the carriage is space for the environmental chamber (not shown in Figure 31) to fit in. Brushes on the inside edge of the environmental chamber will resist the air from flowing out as the carriage movers across the test section.



Figure 31. Side View of the Carriage Assembly

Additional components of the upper frame are shown in Figure 32. In order to move the carriage when there is no bridge deck below it, return rollers support the weight of the carriage on the bottom flange of the beams. Energy absorption cylinders are mounted to both the upper carriage and the end frames to dissipate the energy of the moving carriage if the control system and/or brakes fail on the Heavy Vehicle Load Simulator.



Upper Carriage Frame

#### Figure 32. End View of the Carriage Assembly

As shown in Figure 33, the large gray wheels on the upper section roll on the rails mounted to the beams. These wheels push against the rails and the load put on the bridge deck is reacted against by the weight of the Heavy Vehicle Load Simulator. Guide rollers are positioned inside and outside the rail on all four corners of the upper carriage. The rollers on one side of the carriage are set to guide the carriage as it travels. The rollers on the opposite side are set slightly farther out from the rail and act as a safety guide in case the rollers on the primary side fail.



Figure 33. Side View of the Carriage Assembly Highlighting the Rail Wheels and Guide Rollers

The upper carriage supports several of the sub-systems on the carriage. Shown in Figure 34 are the pressure gages used to set and read the pressure in the tires and the airbags used to load the axles.



Figure 34. End View of the Upper Carriage Assembly Highlighting Pneumatic items

Vibration is a primary indicator of a system starting to fail. Vibration sensors have been placed on the upper carriage as shown in Figure 35. These sensors are monitored by the control system and if the signal goes above a pre-selected range, the Heavy Vehicle Load Simulator will automatically shut down.



#### Figure 35. Vibration Sensors located on the Upper Carriage Assembly

A top view of the upper carriage is shown in Figure 36 identifying several key components. The air bags used to load the system are connected to a large tank providing additional volume for the pressurized nitrogen to occupy. This extra volume prevents an overload of the system if a step function in load occurs, which would cause

the wheels to rise suddenly. For example, if a block of wood is mistakenly left on the bridge deck and the system is started, the wheels can run over the block and compress the gas in the air bags. This sudden loading could cause the bridge to be loaded at a level not anticipated for the test or may cause damage to the air bags themselves. The additional volume reduces this effect and protects both the test section and the equipment.

The carriage control box houses the electronics used to control the load on the bridge deck, the tire pressure, and monitor the safety systems on the carriage. All this data is provided to the wireless communication system. Also shown in the figure are the locations of the optical sensor target, tire and air bag solenoids, and the nitrogen supply tank.



Figure 36. Top View of the Upper Carriage Assembly

Electrical power is provided to the carriage through an electrical bus bar. Figure 37 shows the location of the bus bar and the trolley that rides along the bus bar as it travels with the carriage. This system provides 120 volt electricity to the carriage.



Figure 37. Top View of the Upper Carriage Assembly Highlighting the Bus Bar and Bus Bar Trolley

The lower frame assembly is shown in Figure 38 and Figure 39. The lower frame is where the tires, axles, air bags and swing arms are attached to the Heavy Vehicle Load Simulator. Truck tires were selected based on the peak load of 7,500 pounds per tire. The axles are rated for 30,000 pounds each. The swing arms and air bags work together to keep the load at the proper level while maintaining constant contact with the bridge deck.



Figure 38. End View of the Lower Carriage Assembly



#### Figure 39. End View of the Lower Carriage Assembly Showing the Axle and Air Bags

Proper alignment of the tires on the carriage is important for maintaining low side loads on the Heavy Vehicle Load Simulator and preventing pre-mature wear of the tires. Figure 40 and Figure 41 show the location of the swing arms and the axle alignment system used to adjust the position of the tires relative to the carriage. The axles are properly aligned at delivery and should rarely require adjustment by the operator.



Figure 40. Side View of the Lower Carriage Assembly Showing the Swing Arms and Pivot Pins



Figure 41. Bottom View of the Lower Carriage Assembly Highlighting the Axle Clamp and Alignment System

#### Load Ramps

There are two ramps that extend from each end frame to the bridge deck. These ramps are used for acceleration and deceleration of the load carriage. They are normally enclosed in the end frame environmental chamber. Each ramp must be installed, lined up with the carriage and bridge deck, and secured in place before testing begins. After testing, they must be raised and secured prior to using the rail carts.





#### **ENVISIONED EXPERIMENT PROTOCOL**

#### **Physical Loading**

According to the AASHTO-LRFD Bridge Design Specification (section C3.6.1.2) the estimated maximum daily truck traffic per lane on an interstate bridge is 4,000 trucks. During repeated environmental loading cycles, the Heavy Vehicle Load Simulator will apply approximately 17,500 truck passes per day at 60,000 lbs, or 30,000 lbs per axle, which far exceeds the legal truck weight limit. Research supports the fact that overweight trucks cause significantly more damage to highway infrastructure than legal or underweight trucks and passenger vehicles. This is universally accepted. It is also accepted that the damage imposed is nonlinear such that significantly more severe damage occurs as the weight increases. Combining simulated high-volume significantly overweight truck loading with environmental loading cycles in a condensed timeframe will accelerate deterioration of the test bridge specimens. Compared to normal wearing conditions, the Heavy Vehicle Load Simulator will be able to accelerate deterioration at a rate 30 times faster than *in situ*; however, taking into account the complex interactions at play, plus the overweight loading, it is likely that this rate will be even higher.

#### **Environmental Loading**

Bridge deterioration—specifically in the forms of concrete deck delamination and spalling – occurs through a variety of complex phenomena that are mainly attributed to water and deicing salts infiltrating the concrete. Formation of cracks in concrete and areas with shallow cover expedites exposure of rebar to chloride ions in salts, which will break down a protective passive film on the rebar surface and initiate corrosion. In addition, concrete scaling caused by formation of ice sheets or lenses near the deck surface creates superficial deterioration and in many cases a more severe freeze/thaw damage that makes the concrete even more vulnerable to continuous salt penetration.

During elevated temperatures in the summer, penetrated salts, heat, rain, and high humidity further increase the rate of corrosion. Rust on the corroded rebar expands and creates additional cracks that allow water and salts to penetrate deeper into the concrete. During the next winter cycle, trapped water freezes and exacerbates the problem with newly added deicing salts. Truck traffic loads on the bridge cause deck deflections, which creates and opens even more cracks. The stress exerted by traveling vehicles, particularly heavy trucks, accelerates deterioration by pulling delaminated concrete from the deck and creating potholes or spalling.

The proposed freeze/thaw/heat cycles, combined with wheel loading, will produce accelerated bridge deterioration through realistic failure mechanisms. This is how the process is envisioned:

**Step 1:** An ambient exposure cycle starts. Wheel loading will induce hairline cracks in the test concrete. Ambient exposure 25°C (77°F) for 2 days **Step 2:** Freeze exposure cycle starts. Periodic salt sprays will apply chloride ions on the concrete surface, which will then be absorbed through concrete surface, especially through cracks. Repeated exposures to freezing cycles will cause surface scaling. Freezing exposure with periodic salt spray -18°C (0°F) for 5 days **Step 3:** Thawing exposure cycle will follow. This period will provide an opportunity for freezing thermal loading to be released, leaving new cracks open for additional liquid and chemicals to enter the structural element. "Low" ambient-thawing exposure 20°C (68°F) for 2 days

**Step 4:** Once thaw exposure cycle is complete, another cycle of extreme thermal loading will follow. A hot and humid exposure cycle representing a typical summer will increase the rate of corrosion significantly due to elevated electrochemical activities. In addition, corrosion of rebar in concrete will increase as concrete resistivity decreases by absorbing humid ambient air. The cycle will conclude with hot and humid exposure with constant UV rays 40°C (104°F) RH for 5 days

This four-step cycle will be repeated until a predetermined state of deterioration is achieved.

By accelerating the deterioration processes researchers will be able to understand and analyze the complex deterioration phenomena that eventually lead to decay and potential failure of bridge elements including: decks (excessive wearing of traveling surface, corrosion of rebar, potholes, spalling); deck protective systems (waterproofing membranes, overlays, concrete sealers, crack sealers, corrosion inhibitors); deck joints; bearings; joint compounds; advanced reinforcing/structural materials; steel protective coatings; high-performance steel; weathering steel; tensioned high-strength structural wires (post-tensioned, pre-tensioned, cable-stayed, suspension cables); and comprehensive repair materials and systems or procedures. Accelerated testing in the Heavy Vehicle Load Simulator also will facilitate rapid but effective validation of new technologies and advanced materials. In addition, various types of NDE technologies and health monitoring sensors also could be evaluated in conjunction with progressive changes toward more deteriorated states of test specimens.

## **Experiment Protocols**

Experiments will resemble field testing of inventory bridges with the exception that instruments and equipment will also be subjected to the accelerated physical and environmental loading imparted on the superstructure sample. Capturing the changes in the specimen, which will occur in a rapidly compressed timeframe will require close investigation and selection of robust instruments that will capture in-situ as well as environmental conditions. The following is a partial list of considerations:

- 1. Deck surface and internal temperature
- 2. Deck and ambient relative humidity
- 3. Corrosive activity in rebar
- 4. Chloride content in brine and deck ingress
- 5. Restrained shrinkage in top mat rebar
- 6. Restrained shrinkage in other areas of concrete deck (near shear studs, top flanges, stay in place forms, etc)
- 7. Superstructure stresses/strains
- 8. Bearing reactions

## Health and Safety Protocols

Operations of this one-of-a-kind, 24/7 laboratory detailed procedures to safely and efficiently conduct experiments. Volume II of this Final Report presents a set of standard operating procedures (SOP) to outline day-to-day operation and use. The SOP ensures safety of researchers, efficient use of equipment, proper alignment and sealing of equipment components, proper installation of external instruments, proper hookup of utilities and external instruments, and appropriate shutdown procedures.

## **Future Work**

The Heavy Vehicle Load Simulator Lab studies—designed to address the most prominent deterioration issues—can produce meaningful, short-term deployable results and immediate recommendations on structural system products and practices. It is envisioned that future work can be conducted in three stages.

During **Stage I**, researchers can focus on determining the optimum thermal and mechanical cycles to apply to conventional bridges that will replicate 15-year deterioration within 6 months. Researchers would continually calibrate and refine the operational parameters of the environmental chamber during this stage.

First, researchers would determine a baseline concrete mixture that maximizes corrosion in rebar by testing four different concrete mix designs. The concrete mixture could be modified to create predictable failure mechanisms. Modifications could include using a higher water/cement (w/c) ratio, no using pozzolanic admixtures, and/or reducing or eliminating air entrainment and other chemical admixtures. The purpose would be to produce test slabs that have consistent material properties and therefore eliminate external variables relating to base materials. Systematically, researchers would narrow mixture parameters to a single optimum mixture that maximizes cracking and rebar corrosion in six months. This mix design would serve as the baseline concrete mix design for future tests. For example, the mix could be w/c = 0.45, no pozzolanic admixtures or other chemical admixtures, and uncoated rebar. This would represent a mix design that has typically been used for older decks during the past 40 years. To further simulate typical construction practice, the deck surface would be scored with transverse grooves (tining) prior to hardening. By minimizing variables, researchers could gain a more comprehensive understanding of the effects individual materials parameters in response to thermal and mechanical loadings and thereby facilitate future tests that better align with real-world performance.

By developing quantitative, measurable indices that strongly correlate to actual bridge performance, protocols would be established for controlled realistic (but accelerated) operational conditions. This would enable scientific study to clearly establish the near-term influences and compounding effects of various inputs and parameters on long-term bridge performance.

Typically, decks deteriorate in localized areas where concrete cover is shallow and/or excessive cracks form. Simply put, when rebar is too close to the surface it corrodes more quickly. By varying the depth of rebar in the specimens the researchers would simulate a normal quality deck section and a poorly constructed section as would be experienced under real world conditions. In some sections of a deck slab, rebar would be placed at the typical depth of two inches below the concrete surface. In other areas, the rebar could be "raised" to a depth of one inch from the surface to simulate faulty or deficient bridge deck construction, which is still a common problem. An appropriate combination of normal and lesser cover would be used under the wheel paths. By controlling the location and the depth of the rebar while eliminating other variables, this critical deterioration mechanism (rebar corrosion) could be indexed, quantified, and measured.

**Stage II** would be dedicated to testing short-term corrosion performance of reinforcing materials such as uncoated "black" rebar, epoxy-coated bar, duplex epoxy-coated bar, hot-dip galvanized bar, stainless steel-clad bar, solid stainless steel bar, and other alternative corrosion-resistant bars. Currently, there are 13 types of commercial rebar materials produced in the world. Rebar testing is an urgently needed research subject

suggested by bridge designers and maintenance engineers through LTBP interviews and other public forums. Test bridge decks could be cast using the same standard concrete mixture developed in Stage I, but each with a different type of reinforcing steel, and then subjected to the same environmental and wheel loading conditions previously described.

**Stage III** study could focus on the durability of various deck protective systems including waterproofing membranes, different types of overlays, corrosion inhibitors, concrete sealers, and crack sealers. Since there is evidence regarding satisfactory use of waterproofing membranes and overlays to extend the service life of decks, the primary interest here would be to compare the performance of these protective systems with respect to an uncoated "control" deck. Furthermore, evaluation of steel girders, steel protective coating systems, bearings, and deck joint systems could be evaluated in parallel studies.

## **Technology Deployment**

The infusion of NDE, temperature, strain, and other critical data that will be borne out of this program will serve to inform, in a rapid manner, bridge managers and modelers in the development of increasingly accurate deterioration algorithms. Corrections will be made, which will refine the models and funding charts relied-upon by decision-makers to maintain their bridge inventory.

Initially, the team will focus on calibrating and validating the equipment. As a one-of-akind, nowhere in the world, world class facility; it is expected that the initial run will require tweaking and modification in order to optimize system performance. While the goal of the initial test specimen isn't explicitly to serve as a validation; the slab is envisioned to carry similar properties to those used in the equipment design. Critical characteristics include the 50-foot span, 20-foot width and 3-foot deep rolled girders. Beyond these characteristics, the team has a wealth of freedom to experiment within the slab to introduce interesting features that undoubtedly will produce realistic and valuable data. One Initial thought includes building-in poor construction practices that lead to underperforming decks. Through this type of experiment, the team can illustrate how evident poor practices can be in the early-age deterioration of bridge decks.

These early results will re-emphasize quality control practices, as well as potential improvements in construction practices. Future field implementation may concentrate on material optimization, improved detailing, new construction techniques and further quality control recommendations. The laboratory will reflect bridges in a real-world environment viewed through the prism of compressed time. Researchers will develop innovations directly tied to the harsh environment practicing engineers are required to consider in their designs. The team envisions this approach as a superhighway for technological bridge engineering advancement.

#### CONCLUSION

Within the next decade, substantial bridge maintenance and replacement will be necessary, as will ongoing highway rehabilitation. These efforts will significantly affect congestion and commerce, negatively impacting the competitiveness of our nation's manufacturing sectors, shipping/trucking capabilities, and port/maritime operations.

The Heavy Vehicle Load Simulator will be an internationally recognized, preeminent facility for the accelerated life-cycle testing and validation of a broad range of current and emerging bridge and pavement technologies—similar to Underwriters Laboratories—for bridge and pavement materials, technologies, and processes. The knowledge gained in the Heavy Vehicle Load Simulator will directly assist owners in decision making and management of their transportation assets. The Heavy Vehicle Load Simulator will be valuable to all those engaged in the design, development, supply, construction, and maintenance of bridge and pavement infrastructure worldwide.

The Heavy Vehicle Load Simulator will address the nation's needs with respect to supporting infrastructure health and rapidly evaluating and standardizing new technologies for assessment of deterioration, safety, new materials, and construction techniques to enhance the preservation and life spans of our nation's bridges.