Missouri Demonstration Project:

Replacement of Three Bridges Using Hybrid-Composite Beam Technology

Final Report
March 2013

U.S. Department of Transportation
Federal Highway Administration

FOREWORD

The purpose of the Highways for LIFE (HfL) pilot program is to accelerate the use of innovations that improve highway safety and quality while reducing congestion caused by construction. LIFE is an acronym for Longer-lasting highway infrastructure using Innovations to accomplish the Fast construction of Efficient and safe highways and bridges.

Specifically, HfL focuses on speeding up the widespread adoption of proven innovations in the highway community. “Innovations” is an inclusive term used by HfL to encompass technologies, materials, tools, equipment, procedures, specifications, methodologies, processes, and practices used to finance, design, or construct highways. HfL is based on the recognition that innovations are available that, if widely and rapidly implemented, would result in significant benefits to road users and highway agencies.

Although innovations themselves are important, HfL is as much about changing the highway community’s culture from one that considers innovation something that only adds to the workload, delays projects, raises costs, or increases risk to one that sees it as an opportunity to provide better highway transportation service. HfL is also an effort to change the way highway community decisionmakers and participants perceive their jobs and the service they provide.

The HfL pilot program, described in Safe, Accountable, Flexible, Efficient Transportation Equity Act: A Legacy for Users (SAFETEA-LU) Section 1502, includes funding for demonstration construction projects. By providing incentives for projects, HfL promotes improvements in safety, construction-related congestion, and quality that can be achieved through the use of performance goals and innovations. This report documents one such HfL demonstration project.

Additional information on the HfL program is at http://www.fhwa.dot.gov/hfl

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16. Abstract
As part of a national initiative sponsored by the Federal Highway Administration under the Highways for LIFE program, the Missouri Department of Transportation was awarded a $1.5 million grant to demonstrate the use of proven, innovative technologies for accelerated bridge construction. This report documents the use of hybrid-composite beam (HCB) technology to accelerate the replacement of three bridges at various locations in Missouri. Using innovations on these projects increased safety, enhanced quality, and resulted in structures that will provide increased longevity and lower maintenance costs for the people of Missouri.

Using hybrid-composite technology increased the initial cost of the beams from 30 to 80 percent on the three projects. This increase is due in part to the cost of transporting the beams from the factory in Maine, a haul distance of more than 1,400 miles. The use of portland cement concrete (PCC) decks with HCB also added to the initial costs. Considering the future maintenance cost savings associated with PCC decks, the net increase in life cycle costs ranged from 23 to 74 percent on these three projects. It is assumed that the experience gained from this project will allow for more routine use of this technology in the future if a more cost-effective source for the product becomes available.

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SI* (MODERN METRIC) CONVERSION FACTORS				
APPROXIMATE CONVERSIONS TO SI UNITS				
Symbol	**When You Know**	**Multiply By**	**To Find**	**Symbol**
		LENGTH		
(none)	Mil	25.4	micrometers	µm
in	Inches	25.4	millimeters	mm
ft	Feet	0.305	meters	m
yd	Yards	0.914	meters	m
mi	Miles	1.61	kilometers	km
		AREA		
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yards	0.836	square meters	m^2
ac	Acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
		VOLUME		
fl oz	fluid ounces	29.57	millimeters	mL
gal	Gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
		NOTE: volumes greater than 1000 L shall be shown in m^3		
		MASS		
oz	Ounces	28.35	grams	g
lb	Pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
		TEMPERATURE (exact degrees)		
°F	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	°C
		ILLUMINATION		
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela per square meter	cd/m^2
		FORCE and PRESSURE or STRESS		
lbf	Poundforce	4.45	Newtons	N
lbf/in^2 (psi)	poundforce per square inch	6.89	kiloPascals	kPa
k/in^2 (ksi)	kips per square inch	6.89	megaPascals	MPa
		DENSITY		
lb/ft^3 (pcf)	pounds per cubic foot	16.02	kilograms per cubic meter	kg/m^3
APPROXIMATE CONVERSIONS FROM SI UNITS				
Symbol	**When You Know**	**Multiply By**	**To Find**	**Symbol**
		LENGTH		
µm	Micrometers	0.039	mil	(none)
mm	Millimeters	0.039	inches	in
m	Meters	3.28	feet	ft
m	Meters	1.09	yards	yd
km	Kilometers	0.621	miles	mi
		AREA		
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	Hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
		VOLUME		
mL	Milliliters	0.034	fluid ounces	fl oz
L	Liters	0.264	gallons	gal
m^3	cubic meters	35.314	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
		MASS		
g	Grams	0.035	ounces	oz
kg	Kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T
		TEMPERATURE		
°C	Celsius	1.8C+32	Fahrenheit	°F
		ILLUMINATION		
lx	Lux	0.0929	foot-candles	fc
cd/m^2	candela per square meter	0.2919	foot-Lamberts	fl
		FORCE and PRESSURE or STRESS		
N	Newtons	0.225	poundforce	lbf
kPA	kiloPascals	0.145	poundforce per square inch	lbf/in^2 (psi)
MPa	megaPascals	0.145	kips per square inch	k/in^2 (ksi)

*SI is the symbol for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380. (Revised March 2003)

ACKNOWLEDGMENTS

The project team would like to acknowledge the invaluable insights and guidance of Federal Highway Administration (FHWA) Highways for LIFE Team Leader Byron Lord and Program Coordinators Mary Huie and Ewa Flom, who served as the technical panel on this demonstration project. Their vast knowledge and experience with the various aspects of construction, technology deployment, and technology transfer helped immensely in developing both the approach and the technical matter for this document. The team also is indebted to Ken Foster of the FHWA Missouri Division for his effective coordination effort and to Missouri Department of Transportation Safe and Sound Project Director Ken Warbritton, Safe and Sound Structural Liaison Engineer Stacy McMillan, and Safe and Sound Research Engineer John Wenzlick. The project team was instrumental in making this project a success and provided the information that helped shape this report.

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ABBREVIATIONS AND SYMBOLS

AADT	annual average daily traffic
AC	asphaltic concrete
FHWA	Federal Highway Administration
HCB	hybrid-composite beam
HfL	Highways for LIFE
LCCA	life cycle cost analysis
MoDOT	Missouri Department of Transportation
MOT	maintenance of traffic
OSHA	Occupational Safety and Health Administration
PCC	portland cement concrete
PDO	property damage only
SAFETEA-LU	Safe, Accountable, Flexible, Efficient Transportation Equity Act: A Legacy for Users
VOC	vehicle operating cost
vpd	vehicles per day

INTRODUCTION

HIGHWAYS FOR LIFE DEMONSTRATION PROJECTS

The Highways for LIFE (HfL) pilot program, the Federal Highway Administration (FHWA) initiative to accelerate innovation in the highway community, provides incentive funding for demonstration construction projects. Through these projects, the HfL program promotes and documents improvements in safety, construction-related congestion, and quality that can be achieved by setting performance goals and adopting innovations.

The HfL program—described in the Safe, Accountable, Flexible, Efficient Transportation Equity Act: A Legacy for Users (SAFETEA-LU)—may provide incentives to a maximum of 15 demonstration projects a year. The funding amount may total up to 20 percent of the project cost, but not more than $5 million. Also, the Federal share for project may be up to 100 percent, thus waiving the typical State-match portion. At the State's request, a combination of funding and waived match may be applied to a project.

To be considered for HfL funding, a project must involve constructing, reconstructing, or rehabilitating a route or connection on an eligible Federal-aid highway. It must use innovative technologies, manufacturing processes, financing, or contracting methods that improve safety, reduce construction congestion, and enhance quality and user satisfaction. To provide a target for each of these areas, HfL has established demonstration project performance goals.

The performance goals emphasize the needs of highway users and reinforce the importance of addressing safety, congestion, user satisfaction, and quality in every project. The goals define the desired result while encouraging innovative solutions, raising the bar in highway transportation service and safety. User-based performance goals also serve as a new business model for how highway agencies can manage the highway project delivery process.

HfL project promotion involves showing the highway community and the public how demonstration projects are designed and built and how they perform. Broadly promoting successes encourages more widespread application of performance goals and innovations in the future.

Project Solicitation, Evaluation, and Selection

FHWA has issued open solicitations for HfL project applications annually since fiscal year 2006. State highway agencies submitted applications through FHWA Divisions. The HfL team reviewed each application for completeness and clarity, and they contacted applicants to discuss technical issues and obtain commitments on project issues. Documentation of these questions and comments was sent to applicants, who responded in writing.

The project selection panel consisted of representatives of the FHWA offices of Infrastructure, Safety, and Operations; the Resource Center Construction and Project Management team; the Division offices; and the HfL team. After evaluating and rating the applications and supplemental information, panel members convened to reach a consensus on the projects to recommend for approval. The panel gave priority to projects that accomplish the following:

- Address the HfL performance goals for safety, construction congestion, quality, and user satisfaction.
- Use innovative technologies, manufacturing processes, financing, contracting practices, and performance measures that demonstrate substantial improvements in safety, congestion, quality, and cost-effectiveness. An innovation must be one the applicant State has never or rarely used, even if it is standard practice in other States.
- Include innovations that will change administration of the State's highway program to more quickly build long-lasting, high-quality, cost-effective projects that improve safety and reduce congestion.
- Will be ready for construction within 1 year of approval of the project application. For the HfL program, FHWA considers a project ready for construction when the FHWA Division authorizes it.
- Demonstrate the willingness of the applicant State to participate in technology transfer and information dissemination activities associated with the project.

HfL Project Performance Goals

The HfL performance goals focus on the expressed needs and wants of highway users. They are set at a level that represents the best of what the highway community can do, not just the average of what has been done. States are encouraged to use all applicable goals on a project:

- **Safety**
    - Work zone safety during construction—Work zone crash rate equal to or less than the preconstruction rate at the project location.
    - Worker safety during construction—Incident rate for worker injuries of less than 4.0, based on incidents reported via Occupational Safety and Health Administration (OSHA) Form 300.
    - Facility safety after construction—Twenty percent reduction in fatalities and injuries in 3-year average crash rates, using preconstruction rates as the baseline.
- **Construction Congestion**
    - Faster construction—Fifty percent reduction in the time highway users are impacted, compared to traditional methods.
    - Trip time during construction—Less than 10 percent increase in trip time compared to the average preconstruction speed, using 100 percent sampling.
    - Queue length during construction—A moving queue length of less than 0.5 miles in a rural area or less than 1.5 miles in an urban area (in both cases at a travel speed 20 percent less than the posted speed).

- **Quality**
  - User satisfaction—An assessment of how satisfied users are with the new facility compared to its previous condition and with the approach used to minimize disruption during construction.
  - Noise—Tire-pavement noise measurement of less than 96.0 A-weighted decibels (dB(A)), using the onboard sound intensity (OBSI) test method.
  - Smoothness—International Roughness Index (IRI) measurement of less than 48 inches (in) per mile.
  - Durability—An assessment of how composite materials are expected to contribute to increased life and decreased maintenance of the composite structural elements.

REPORT SCOPE AND ORGANIZATION

This report documents the Missouri Department of Transportation's (MoDOT) HfL demonstration project, which involved accelerated removal and replacement of three bridges that were part of the Safe and Sound Bridge Improvement Program. The report presents project details relevant to the HfL program, including innovative contracting, superstructure and substructure design and construction highlights, rapid bridge removal and replacement, HfL performance metrics measurement, and economic analysis.

PROJECT OVERVIEW AND LESSONS LEARNED

PROJECT OVERVIEW

In May 2009, MoDOT awarded a single design-build contract to replace 554 bridges in Missouri. The successful contractor proposed the use of standard construction technology (steel or concrete I-beams, concrete box beam, and voided slabs) on the majority of these projects. MoDOT proposed that three of the structures included in this package be constructed using hybrid-composite beam (HCB) construction to determine if such techniques can be used to speed construction and increase safety on such projects in the future. Three projects were selected in Douglas, Dade, and Reynolds Counties on routes MO 76, MO 97, and MO 49, respectively.

HCBs consist of three main components: an outer shell made from a fiber-reinforced plastic, a compression component provided by filling the arched void formed in the shell with self-consolidating concrete, and a tension component provided by steel strands molded into the bottom flange of the fiber-reinforced shell.

One of the major considerations of the Safe and Sound program is to complete these bridge replacements with minimal inconvenience to the public through increased construction speed. The use of HCB technology allowed the projects to be constructed using smaller cranes to set the beams, fewer trucks to transport the beams to the construction site, and reduced time to set the beams, all attributes that support the HfL philosophy.

DATA COLLECTION

Safety and construction congestion data were collected before, during, and after construction, where appropriate, to demonstrate that accelerated bridge technologies can be used to achieve the HfL performance goals in these areas.

The safety goals for the project included both worker safety and motorist measures. The worker safety goal was an incident rate of 4.0 or less, as reported on OSHA 300 form. No worker injuries occurred during construction. The motorist goal during construction was a crash rate equal to or less than the preconstruction crash rate. No accidents were reported on the Douglas County and Dade County projects, while a single crash happened on the Reynolds County project. This crash was considered more of a traffic violation incident than a work zone safety issue.

Complete closure of the roadway was used where possible to allow the contractor maximum control over the worksite. The average time to complete a bridge under the Safe and Sound program was 42 days, whereas the average construction time using conventional methods on similar-sized structures was 90 to 100 days. Because one of the goals of the Safe and Sound program was to cut construction time in half, it would not be appropriate to compare these three HfL projects to the average construction time of other projects constructed under the Safe and Sound program. However, two of the three projects constructed using HCB were completed in less than half the time of a typical conventional bridge replacement. The third took longer than average because of problems with constructing the piers, but none of the delay was associated with the HCB technology. Even in this case the overall time did not exceed the average construction time for conventional bridge replacement projects.

Because the roadways were closed during construction, it was not possible to measure construction-related congestion in the typical way. Traditionally, the principle component of user cost associated with construction is the increased travel time for the detour and the associated vehicle operating costs (VOC). However, because of the extremely low volume of both the closed and detour routes for these projects, at no time did traffic approach the capacity of the roadways. The use of the composite beams did result in the ability to haul more beams on a single trailer to the jobsite, which reduced delay.

Noise and smoothness were not used as measures of quality on these projects because of the short length of the work and the extreme rural locations.

The durability of the construction is expected to be far above average. The HCB shell is made of a fiber-reinforced plastic that is far more resistant to deterioration than steel or concrete alternatives. The decision was made to gel coat all beam surfaces to protect against ultraviolet radiation, resulting in a beam expected to perform for 75 to 100 years with little or no maintenance.

ECONOMIC ANALYSIS

MoDOT's cost to implement the HCB technology was substantially greater than that of traditional construction methods. The increased cost of the beams alone ranged from about $340,000 to $450,000 per structure, or 30 to 80 percent more than traditional components. Another substantial part of the additional cost is attributable to transporting the beams from the fabricator to the site. While the reduced weight of the beam shells allowed more to be hauled on a single trailer, this was not offset by the initial cost of the HCBs or the fact that the fabricator was located in Maine, more than 1,400 miles from the project sites. This report includes a detailed economic analysis of the individual structures.

LESSONS LEARNED

One advantage of the HCB technology is the ability to set the beams with a much smaller crane. When the beams leave the factory, they consist of a very light fiberglass shell that is filled with concrete either after they are installed on the piers or before delivery to the site. Even when filled offsite, the weight is still significantly less than the standard steel or concrete beams that traditionally would be used. While in the Missouri case larger cranes were already onsite for use in driving pile, in certain areas a smaller, lighter crane would be advantageous.

A learning curve is always associated with implementing any new technology. In this case, the situation was magnified by the fact that all three structures were constructed by different contractors, with limited knowledge transfer between them. MoDOT staff indicated that they see the technology as viable, especially in circumstances where limited space is available for crane erection or where it is advantageous to limit the number of large vehicles delivering beams to the project.

Should the manufacturing of the beams become more regional, reducing time and transportation costs, the technology would become much more viable.

For the Douglas County project, beams were filled at the plant because of concerns about the self-consolidating concrete mix setting during transport to the site, a distance of about 45 miles. Experience in adjusting the mix with plasticizers and extenders gave MoDOT the confidence to fill the beams for the Reynolds County project after setting them on the piers, as originally planned. The beams for the project in Dade County were some of the longest and deepest beams constructed to date. Because of concerns about flow of the self-consolidating concrete through the fiberglass form and the voids that might result, these beams were filled at a plant in Virginia before transit to Missouri.

Although the fills were made offsite in two of the three cases, the beams were still significantly lighter and easier to handle than traditional concrete or steel beams. The reduced weight meant that more beams could be hauled per truck, resulting in less traffic disruption to the site. This could be a significant advantage in a high-traffic urban setting. In either case (filled or empty), setting the beams was extremely easy. Two men could easily move the beams into place.

Several issues were identified with the use of the HCB technology, but many stemmed from the fact that the technology was new to both the State and the contractors involved in the construction. The three structures were constructed by three different contractors, so much of the knowledge gained on one bridge had to be relearned on subsequent structures. This was a result of selecting the projects from the existing pool of Safe and Sound projects.

While the initial cost of the HCB is higher, MoDOT believes that there is a definite advantage to HCB technology in certain locations and under conditions where the need to rapidly set beams with light equipment is needed and where future maintenance needs to be minimized.

CONTRACTING PROCEDURES

All three of the structures selected for replacement using HCB technology were part of the Safe and Sound Bridge Improvement Program that MoDOT launched in 2009. Under the program, MoDOT replaced or rehabilitated 802 bridges during a 3.5-year period. Figure 1shows a map of 554 of these structures that were part of a single design-build contract. The program involved 22 Missouri contractors and more than 100 subcontractors and local material suppliers.

Because the three structures selected for the HfL project were already part of this design-build contract, no special contracting procedures were required. However, the substitution of the HCB technology required numerous special provisions to be negotiated with the prime contractor to substitute for the assumed design of traditional steel or concrete box beam construction. Additional agreements were required between the beam fabricator, the prime contractor, and MoDOT for design, fabrication, and delivery of the beams to the site.

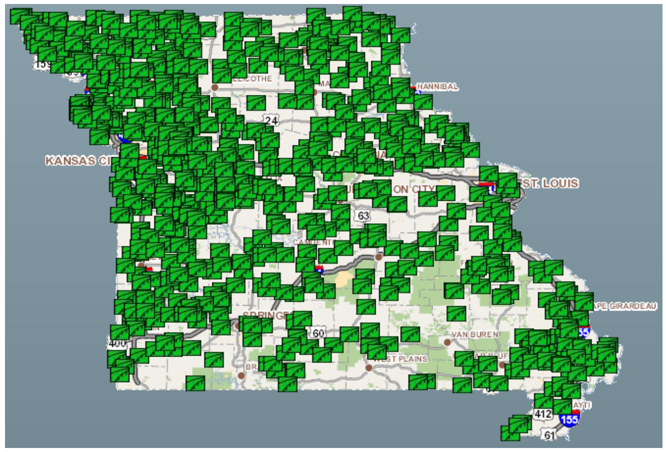

Figure 1. Location of bridges replaced under the MoDOT Safe and Sound program.
(Source: http://safeandsoundmap.modot.mo.gov/flex/safeandsound.html)

DESIGN AND CONSTRUCTION

The design and construction process was successful because of the extraordinary cooperation among the owner, contractor, and manufacturer throughout the process. This was necessary because the three structures selected for the HfL program were pulled from the hundreds that were a part of the single design-build contract. All had already been designed using traditional construction methods when the decision was made to include them in this program. Redesign of the beams was done by the HCB consulting team, who provided guidance to the manufacturer and onsite construction support on all three structures.

PUBLIC INVOLVEMENT

The public was not surveyed specifically on the three bridge replacements discussed in this report. As discussed previously, the structures were constructed by change orders to the existing Safe and Sound contract. The Safe and Sound program featured an extensive public involvement effort, including local public meetings, television news and newspaper coverage, and a Web site for tracking the schedule and progress of individual projects and the program as a whole. Before Safe and Sound, the average time to complete a bridge replacement for structures of this size was about 100 days. The average time to complete a replacement under the Safe and Sound program was 45 days.

CONCLUSIONS

All three projects were completed with no major issues related to the HCB technology. The projects were successful in meeting the goals for safety and construction congestion. All Safe and Sound projects are designed around the concept of construction speed and these projects were no different. While more lead time was required to fabricate and ship the HCBs, no additional time was required for construction. Slightly more time was required to prepare the beams for filling (placing and tying shear steel, for example), but this was offset to some extent by the decreased time required to haul beams to the site and physically set them in place.

Two of the three structures were replaced with no change in location or geometrics. However, the new structures are significantly wider than the existing structures and have updated safety barrier. The third structure, in Dade County, was replaced with a widened deck and updated safety features, and it was constructed slightly downstream of the existing structure to correct geometric issues. As a result of the geometric revisions, safety improvements, and widened structures, all three locations are expected to experience decreased crash rates in the future.

The maintenance activities required on the HCBs are expected to be far less than on conventional beams. The fiber-reinforced plastic shell is inherently corrosion-resistant and offers a service life of 75 to 100 years with little or no maintenance.

PROJECT DETAILS—GENERAL

BACKGROUND

The MoDOT HfL demonstration project consisted of the replacement of three bridges using HCB technology. The projects are located on MO 76 in Douglas County, MO 49 in Reynolds County, and MO 97 in Dade County. The original contract called for the replacement of a bridge on U.S. 60 in Douglas County, but fabrication issues conflicting with the already scheduled closure of the roadway forced the substitution of the Reynolds County location.

All projects are two-lane rural locations with relatively low traffic volumes. All are part of the Safe and Sound program undertaken by MoDOT in 2009 to replace 554 bridges under a single design-build project.

PROJECT DETAILS—MO 76 IN DOUGLAS COUNTY

BACKGROUND

The first of three structures replaced under this demonstration project was a bridge over Beaver Creek on MO 76 in Douglas County. Figure 2 shows the location of the project and the detour route. The detour of about 25 miles (mi) is an increase of about 12 mi over the direct route length.

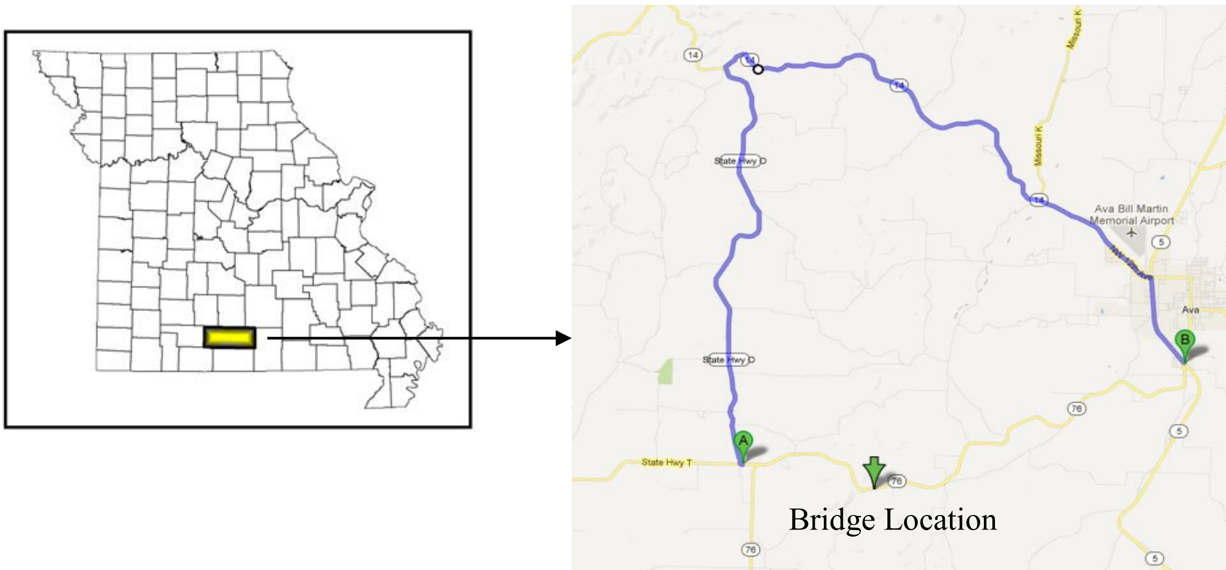

Figure 2. Douglas County project location with detour route highlighted in yellow.

Figure 3 shows the original structure, which consisted of a 176-foot (ft), three-span steel I-beam structure built in 1935. At this location, MO 76 is a rural two-lane facility serving about 2,035 vehicles per day (vpd).

The new structure consists of a three-span, 175-ft deck 30 ft, 8 inches (in) wide with a 28-ft roadway (an increase of 8 ft in roadway width). The new structure was placed on the existing alignment. All three spans consist of 58-ft, 4-in HCB. Construction took from August 15 to November 11, 2011, resulting in a closure of 95 days.

Figure 3. Old structure on MO 76 over Beaver Creek in Douglas County.

HCB Mockup Pour

The use of HCB technology was new to both MoDOT and the contractors involved in the construction. Likewise, the use of self-consolidating concrete to fill the beam molds was not a standard practice. To gain experience with the materials involved, it was decided to construct a half-scale model of one of the beams with a clear acrylic side so that the movement of the concrete through the mold could be observed. In this way, techniques to facilitate introduction of mix and vibration patterns could be developed. The test pour was conducted on August 2, 2011, at the Mountain Grove facility responsible for delivery of the job mix for the MO 76 project. Figures 4 and 5 show the mockup.

Significant time was taken to adjust the mix to the correct slump. The slump test was modified in that the cone was inverted and the diameter of the pool measured after removal. Figures 6 and 7 show the slump testing. Figure 8 shows a second test that involved the placement of a cage around the cone to measure the ability of the aggregate to move around an obstacle.

Figure 4. Half-scale mockup of HCB.

Figure 5. End view of mockup showing location and density of web reinforcement.


Figure 6. Modified slump test.


Figure 7. Slump test results from self-consolidating concrete.

Figure 8. Cage test results of modified slump of self-consolidating concrete.

Figure 9 shows the openings in the top of the beam used for filling, originally sized at 4 in. As a result of the test pour, the opening was increased to 5 in to increase mix flow. Despite the low viscosity of the mix, substantial vibration was required to fill the beam. As long as the mix was in motion, it tended to continue (figure 10). If for any reason the flow stopped—as when moving from one fill hole to another, for example—vibration was required to start it moving again (figure 11).

Figure 9. Filler openings located at one-quarter points along the beam top with steel reinforcing strand visible.

Figure 10. Self-consolidating concrete flowing through the beam arch around reinforcing steel.

Figure 11. Vibrator being used to facilitate mix flow through beam arch.

The plasticizer used in the self-consolidating mix had a life of about 30 minutes before the mix began to set. It was determined that even during the 30-minute life continuous rotation of the drum was required to prevent early setting. Mix in the hopper or hoses of the pump would begin to set almost immediately if flow was interrupted. Since the project location was more than 40 mi from the plant, it was determined that it would be risky to cast the beams in place on the job site; instead, they were cast at the plant and transported.

Figure 12 shows the results of infrared photography used to detect the possibility of voids in the compression arch during filling of the beams.

After analysis, the mockup beam was transported to Sedalia, MO, and placed on display at a MoDOT exhibit at the Missouri State Fair to educate the public on the technology being used on these projects.

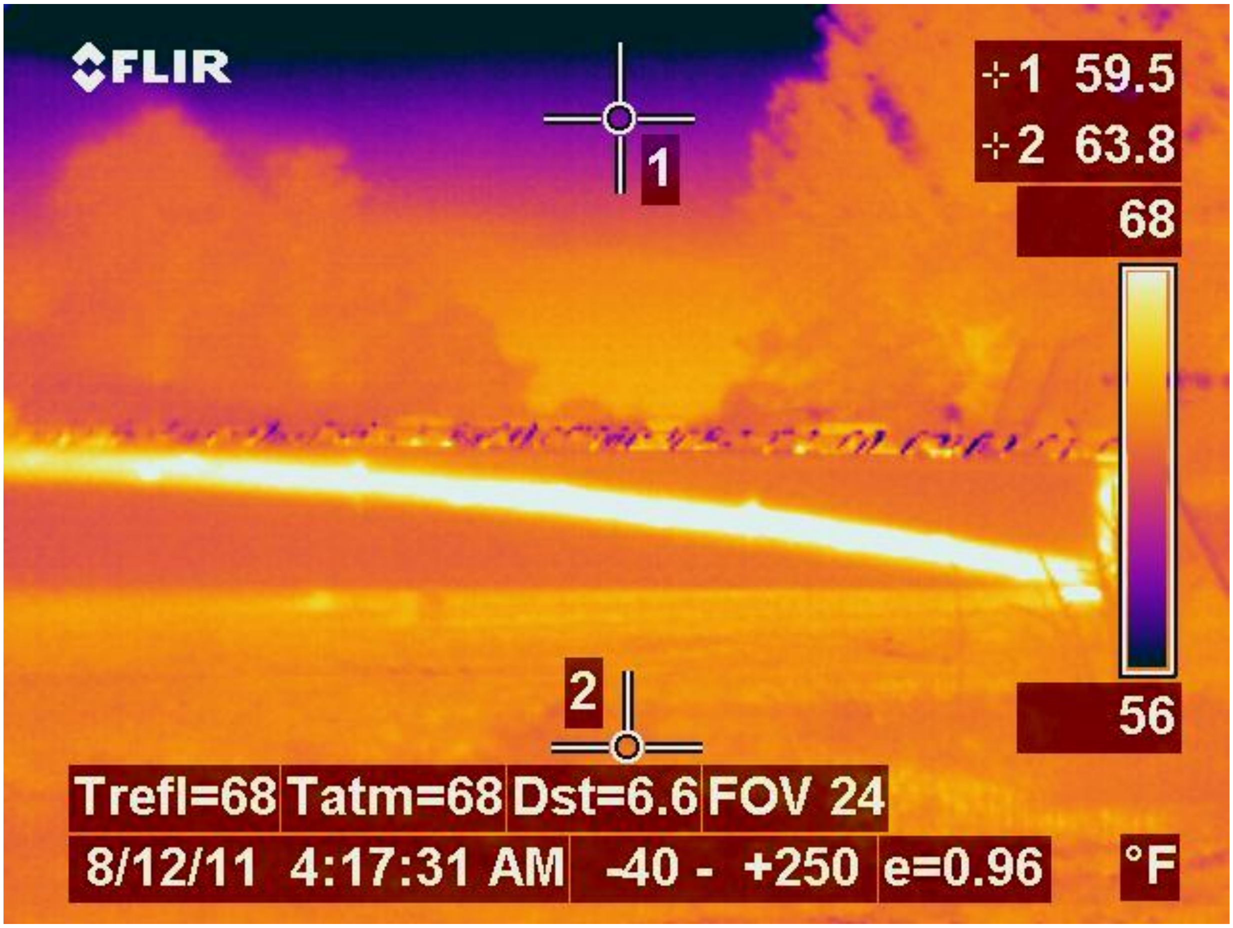

Figure 12. Infrared image of test beam used to detect voids in compression arch pour. (Photo courtesy of Missouri University of Science and Technology)

PREFABRICATED BRIDGE COMPONENTS AND MATERIALS

Traditional construction for a structure of this size and type would be either steel I-beam or prestressed concrete I-girders. The weight of the HCBs used on this project was about 3,400 pounds each empty. Filling the compression arch added about 10,000 pounds. The total weight of 13,500 pounds each is about 40 percent less than traditional steel beams. For this structure, the required 15 beams were filled at the concrete plant and transported to the jobsite. The decreased weight allowed two beams to be transported at a time, resulting in less congestion on the narrow, winding roads of rural Missouri.

Figure 13 shows a cross section of the beams, including the location of the compression arch formed by injection of the self-consolidating concrete.

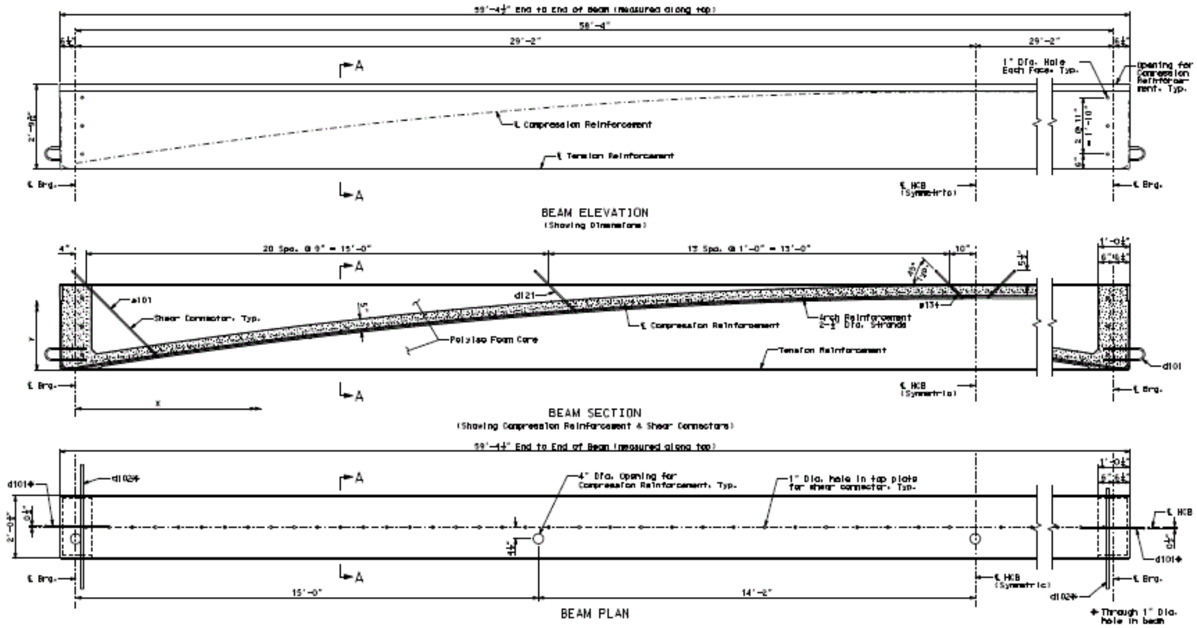

Figure 13. Section view of HCB from construction plans.

SUBSTRUCTURE CONSTRUCTION

The existing substructure was determined to be inadequate to use for the proposed widened structure. Figure 14 shows the placement locations of new steel pipe piers.

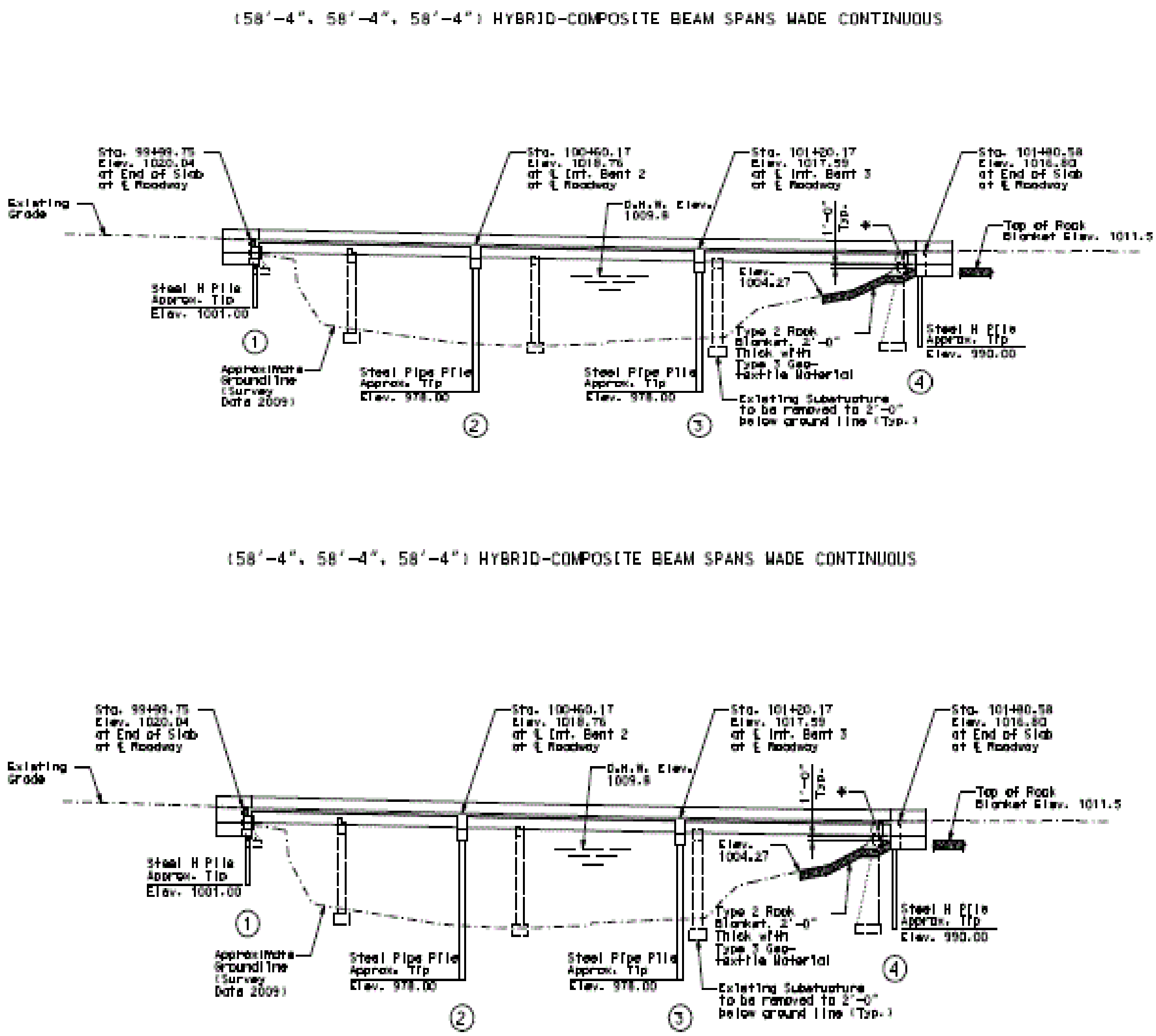

Figure 14. Plan view showing existing and revised pier locations for Douglas County structure.

SUPERSTRUCTURE CONSTRUCTION

The deck replacement consisted of the placement of five HCBs spaced on 6-ft, 4-in centers. The beams were 58 ft, 4 in long and 2 ft, 9 3/16 in deep. On top of the beams was placed a traditional 8.5-in portland cement concrete (PCC) deck with an overall (out to out) width of 30 ft, 8 in, providing a 28-ft roadway width. Figure 15 illustrates the cross sectional dimensions of the new structure.

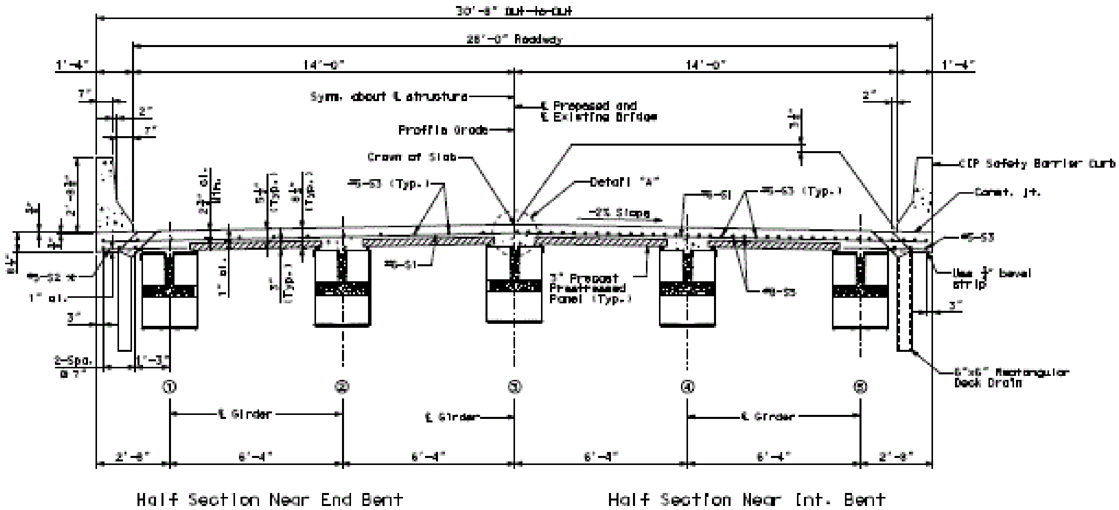

Figure 15. End view cross section of Douglas County structure.

Figure 16. Delivery of beams to Douglas County project.

Figure 17. First beams arriving at the Douglas County site.

Figure 18. First beams lifted from truck and set in place.

Figure 19. First center span beam lifted into position.

Figure 20. Final beam set in place.

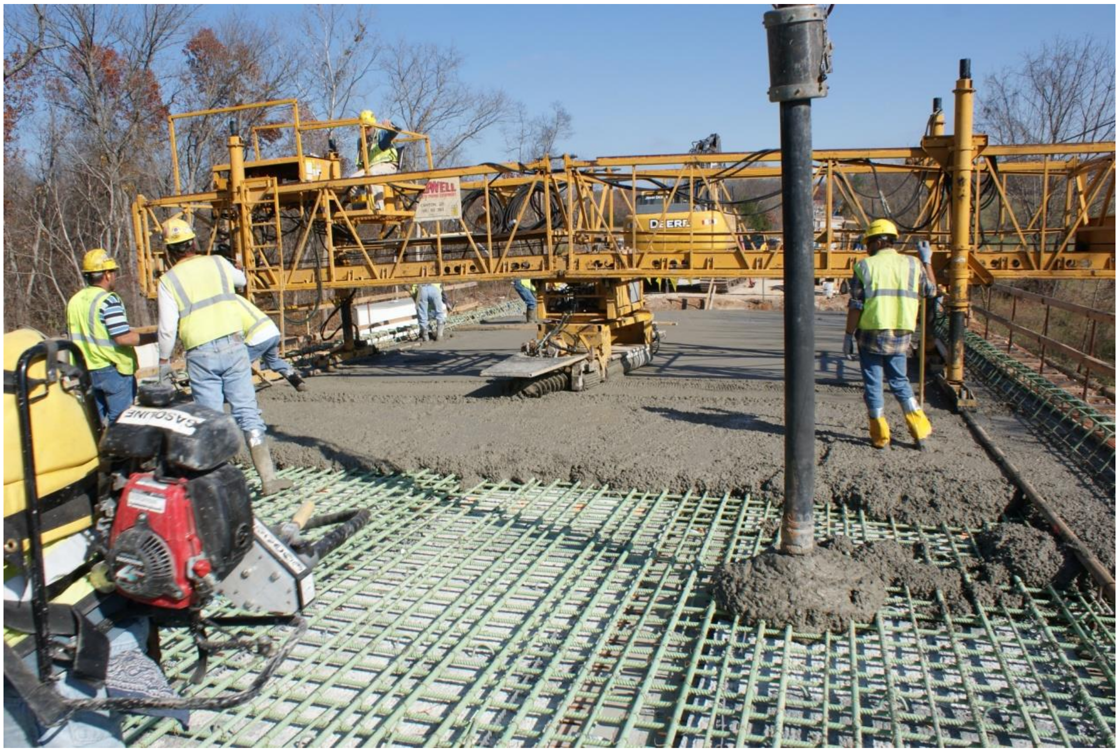

Figure 21. Deck pour on Beaver Creek Bridge.

DATA ACQUISITION AND ANALYSIS

Safety, construction congestion, and quality data were collected before and after construction for this project where appropriate. The primary purpose was to supply the HfL program with sufficient information to support using HCB technology in future applications. The analysis will provide information on the following HfL goals:

- Work zone and worker safety during construction
- Facility safety after project completion
- Faster construction and reduced construction congestion
- Increased consumer satisfaction
- Increased durability of materials and decreased future maintenance costs

This section details specific project data on the HfL goals defined for these areas.

SAFETY

Safety goals for HfL projects are based on worker safety during construction and traveler safety during and after project completion. The worker safety goal is set at a 4.0 or less, as reported on the OSHA 300 form available from the contractor. The public goal is a crash rate equal to or less than the preconstruction crash rate.

No worker injuries were reported on this project.

Because the road was closed completely during construction, there were no road user work zone crashes in a traditional sense. For the purpose of this analysis, the researchers calculated the crash rates before and during construction on the detour routes. It was assumed that 100 percent of the traffic was diverted to the detour routes, and the preconstruction annual average daily traffic (AADT) was added to each leg of the detour route for calculation of the crash rates during the closure period. Tables 1 and 2 show the crash rates for each leg of the detour.

Table 1. Crash rates for original and detour routes before construction, Douglas County project.

		Preconstruction							
				Crashes (3-Year Totals)					
Route	Termini	Length (miles)	Volume (3-year average)	Fatal	Injury	PDO	3-Year Rate	3-Year Rate (Facility Type)	3-Year Rate (Statewide by Route. Designation)
MO 76	Original Route: MO 14 to Route T	11.689	2,101	1	8	21	111.55	189.17	234.98
	(Detour Routes)								
MO 14	MO 76 to Route O	10.287	1,764	0	23	38	306.99	*	234.98
Route O	MO 14 South to Route T	8.619	386	0	2	2	109.79	189.17	227.31
Route T	Route O East to MO 76	0.3599	768	0	1	0	0.00	189.17	227.31

* Statewide rate used for this segment because of mixed roadway type

Table 2. Crash rates for original and detour routes during construction, Douglas County project.

		Closure 8/15/2011 to 11/18/2011 (95 days)						
				Crashes				
Route	Termini	Length	Volume (3-year average)	Fatal	Injury	PDO	Closure Rate	3-Year Rate Before Construction
MO 76	MO 14 to Route T	11.689	N.A.	0	0	0	0	111.55
MO 14	MO 76 to Route O	10.287	3,865	0	4	2	159.22	306.99
Route O	MO 14 South to Route T	8.619	2,487	0	0	0	0	109.79
Route T	Route O East to MO 76	0.359	2,869	0	0	0	0	0

* Statewide rate used for this segment because of mixed roadway type
PDO = property damage only

Local traffic continued on MO 76 up to the construction site. No crashes were reported on these sections of MO 76 or on two of the three detour legs during construction. Four injury and two property damage only crashes did occur on the MO 14 leg of the detour. As seen in table 2, even with the increased traffic volume on the detour routes, the crash rate for this roadway was less than the previous 3-year average, meeting the goals of the HfL program. Future safety is expected to improve as well, because the structure was widened from 20 to 28 ft and substandard railings on the existing structure were replaced with concrete safety barrier curb.

CONSTRUCTION CONGESTION

The standard HfL goal for impact of construction on the public is a 50 percent reduction compared to conventional methods. Historically, MoDOT has averaged between 90 and 100 days to replace a bridge of similar size on a similar roadway. However, with the MoDOT's Safe and Sound rapid bridge replacement program, the average closure duration was 42 days.[1] Full roadway closure was used as the maintenance of traffic (MOT) strategy on about 96 percent of the bridge projects under this project.

The closure on this replacement was 95 days. While this did not meet the HfL goal of a 50 percent reduction, the longer-than-expected construction time was not attributed to the HCB innovations. The construction delay was associated with unforeseen site conditions and the construction of the piers.

QUALITY

The inherent corrosion resistance of the HCB fiberglass shell is expected to result in a very low-maintenance bridge that will not rust, crack, or spall like conventional concrete beams or require painting like a steel beam. The service life of the HCB is expected to be in the range of 75 to 100 years.

Although it has a higher initial cost, the PCC deck is also expected to result in lower future maintenance costs.

This technology has a possible environmental benefit if large-scale use becomes common. The volume of concrete used in an HCB is about 80 percent less than that in a prestressed concrete girder. Given that the production of portland cement is one of the largest contributors to the carbon footprint of the construction industry, a shift to this type construction could have a positive environmental impact.

USER SATISFACTION

MoDOT did not conduct a user satisfaction survey as part of this project. However, as with all Safe and Sound projects, extensive preconstruction public involvement and education were conducted. This was especially true in the case of road closures where significant detours were required. While MoDOT received some negative comments on the duration of the closure, the delay had nothing to do with the HCB technology.

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[1]Missouri Department of Transportation, Completion of Safe & Sound, Connections News Article, November 15, 2012 http://www.modot.org/newsandinfo/connections/documents/Nov.14-2012.pdf

ECONOMIC ANALYSIS

In addition to promoting improvements in safety, construction-related congestion, and quality, the value of the innovations is also important. This value can be assessed by comparing the cost of the HfL technology to the cost of a project constructed using traditional methods. Traditionally, bridge replacements of this size use either steel I-girder or prestressed concrete I-beam construction.

CONSTRUCTION COSTS

The original design for this structure using prestressed concrete beams resulted in an estimated cost of $218 per square foot. This amounts to an estimated total cost of $1,518,767 for HCB and $1,169,933 for prestressed concrete beams. Modification to use the HCB technology resulted in a final cost of about $283 per square foot, an increase of about 30 percent.

For this structure, the additional construction costs with the use of HCB were $329,072. This cost differential included the HCB cost of $306,600, a design cost of $81,070, a construction engineering cost of $13,245, a delivery charge of $32,340, and a mobilization cost of $29,222, for a total of $462,477. The redesign and the addition of the deck components, coupled with a credit for the unused beams, resulted in a total change order credit of $133,405. The net increase in construction costs with the use of HCB was $329,072.

LIFE CYCLE COSTS

The baseline scenario called for prestressed concrete beams to be placed side to side with an asphaltic concrete (AC) wearing surface (with a membrane) applied directly to the beam flanges. This was not considered a viable option for the HCBs. Because of this, the redesign included the addition of a traditional concrete deck. This redesign influenced the design and size of the HCBs because of the increased weight of the deck.

A life cycle cost analysis was performed to capture the cost impact of the differences in performance between an AC wearing course and a concrete deck. The expected service life of an AC wearing course was 7 years. The rehabilitation of an AC wearing course would involve mill and overlay every 7 years at an estimated cost of $38.5 per square yard (including $13.5 and $25 per square yard of milling and overlay, respectively). At the end of 28 years, the AC wearing course would need a complete removal and reapplication of membrane. The estimated cost of complete removal and replacement was $80 per square yard (including $55 per square yard of membrane reapplication and $25 per square yard of overlay). With the as-built case, the traditional concrete deck involved 15 percent of half-sole repair at $50 per square yard and a seal at $4 per square yard. The estimated life cycle costs for both baseline and as-built cases are in table 13.

Rehabilitation of asphalt overlays or deck repair would not require full roadway closure detours. Flagger operations would be adequate for MOT on prevailing low-volume traffic conditions with no significant delays anticipated during future bridge deck repairs, so future road user costs were not considered in the life cycle cost analysis.

The estimated life cycle costs were discounted to present values using a long-term 30-year discount rate of 3.0. The period chosen for this analysis was 45 years. Appropriate salvage values were applied at the end of 45 years for both cases. Both the discounted values and the net present value are in table 3.

Table 3. Life cycle cost analysis of bridge deck for the Douglas County project.

Year	Description	Baseline—AC wearing course with membrane		As-built—PCC deck	
		Undiscounted Costs	**Discounted Costs**	**Undiscounted Costs**	**Discounted Costs**
7	AC mill and overlay	$22,957	$18,666		
14	AC mill and overlay	$22,957	$15,177		
21	AC mill and overlay	$22,957	$12,341		
28	AC remove and replace	$22,957	$10,034		
30	PCC 15% half-sole repair			$40,608	$16,730
35	AC mill and overlay	$22,957	$8,159		
42	AC mill and overlay	$22,957	$6,634		
45	Salvage	-$13,119	-$3,469	-$20,304	-$5,369
Net Present Value			$67,541		$11,361
Difference in future costs		**$56,180**			

DETOUR/USER COST

A full road closure was implemented to facilitate bridge replacement. This required all traffic normally using those routes to use an alternative route while the roadway was closed.

Figure 2 illustrates the normal route and main assumed alternative route for the project. Table 4 illustrates both the traffic volumes (AADT, vpd) and distances of travel required using the primary and alternative routes. The low traffic volumes on the alternative routes implied that the effects of traffic diverting to those routes would be negligible.

Consequently, the only travel impacts would be the additional travel time required by those diverting from the primary route to the alternative route. The posted speed limit on the facility was 55 miles per hour (mi/h). Inspection indicated that the typical operating speed was about 50 mi/h.

The time to complete the construction was considered the same as required for the conventional design of prestressed concrete beams, so no comparison of VOC was made between the as-built and baseline scenarios.

TRAVEL TIME COMPARISON RESULTS

An assumption of a 50 mi/h operating speed implies a unit travel time of 1.2 minutes per mile. This unit travel time can be applied to the increased travel distances for each alternative route compared to the primary route to estimate the mobility impacts of the full road closures on a per-vehicle basis. Multiplying by the primary route AADT provides a per-day impact measure. Table

5 presents the results of this analysis. Overall, the mobility impact of the full road closure was minimal. Travel time increased by about 9.0 minutes per vehicle. Summed over all of the traffic diverting each day, the detour resulted in 305.3 vehicle-hours of additional travel time per day of closure.

There was no actual travel time cost differential for the use of HCBs in the construction. The time to complete the construction was considered the same as required for the conventional design of prestressed concrete beams, so no comparison of VOC was made between the as-built and baseline scenarios.

Table 4. Volume and travel distance of primary and alternative routes for the Douglas County project.

Route	Primary Route		Alternative Route		Increased Travel Distance on Alternative Route (mi)
	AADT (vpd)	Distance (mi)	AADT (vpd)	Distance (mi)	
MO 76	2,035	11.7	350-2,000	19.2	7.5

vpd = vehicles per day

Table 5. Mobility impacts of full road closures for the Douglas County project.

Route	AADT Diverting (vpd)	Increased Travel Distance (mi)	Increased Travel Time per Vehicle (min)	Daily Increase in Travel Time (vehicle-hours)
MO 76	2,035	7.5	9.0	305.3

vpd = vehicles per day

SAFETY

As noted earlier, only six crashes were reported during the road closure. Because it is impossible to know if the crashes were a part of the normal traffic or the diverted traffic, it is impossible to determine if they were related to the construction. Because the closure duration would have been about the same for construction with the HCBs as for the baseline construction, it can be assumed that the safety costs for either would be offset, resulting in a cost differential for the HfL innovation of zero.

COST SUMMARY

The use of HCB over prestressed beams resulted in an increased cost of $329,072 for construction. The use of a PCC deck was required with HCB, while the AC overlay of the beam flanges would have been the conventional choice with prestressed box beams. While resulting in higher initial cost, the PCC deck is expected to have lower future maintenance costs than the AC overlay, resulting in net future cost savings of $56,180 (net present value) over a 45-year analysis period. To summarize, the use of HCB on this project resulted in a net cost increase of $272,892, or 23.3 percent of estimated baseline costs.

PROJECT DETAILS—MO 49 IN REYNOLDS COUNTY

BACKGROUND

The second of the three structures replaced under this demonstration project was a bridge over Ottery Creek Overflow on MO 49 in Reynolds County. The original structure consisted of a 103-ft, three-span steel I-beam structure with a 20-ft roadway built in 1934. At this location, MO 49 is a rural two-lane facility serving about 382 vpd.

Figure 22 shows the detour used while the road was closed for construction. The detour of about 21.3 mi is an increase of only about 1.15 mi over the direct route length. Figure 23 shows the project site.

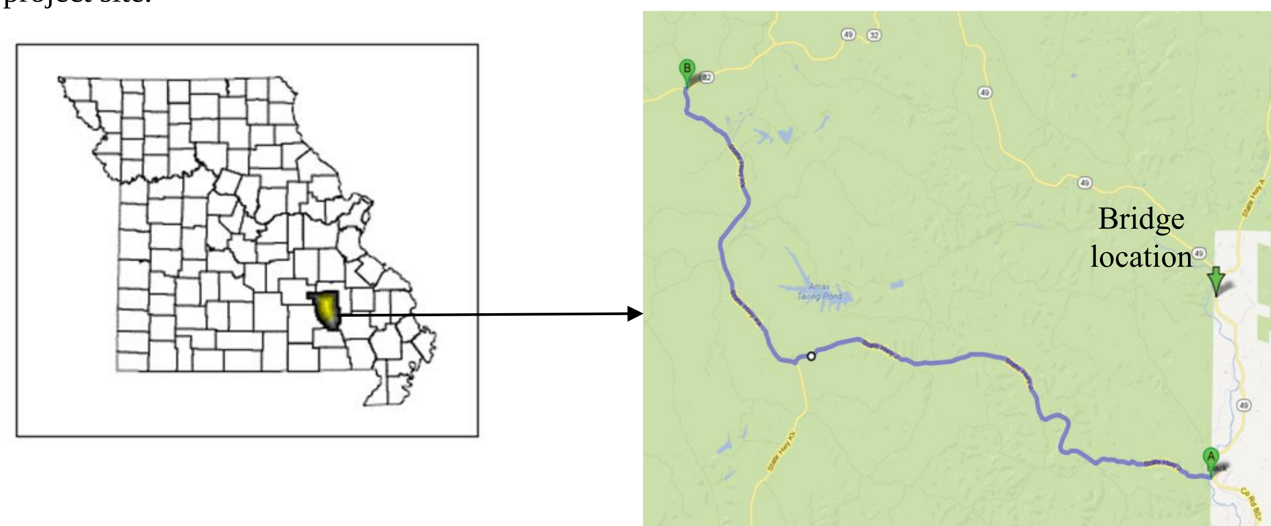

Figure 22. Reynolds County project location, with detour route highlighted in yellow.

Figure 23. Existing structure on MO 49 over Ottery Creek Overflow in Reynolds County.

The new structure consists of a two-span bridge, 101 ft, 2 in long and 26 ft, 8 in wide, providing a 24-ft roadway on the same alignment. Both spans consist of 48-ft, 6-in HCBs. Construction took from June 11 to August 9, 2012, resulting in a closure of 59 days.

PREFABRICATED BRIDGE COMPONENTS AND MATERIALS

Traditional construction for a structure of this type would be either steel I-beams or prestressed concrete I-girders. For this structure, 12 HCBs with a depth of 2 ft, 5/8 in were required. Beams were set empty and filled onsite. Concrete was supplied from a plant in Viburnum, MO, and transported to the jobsite about 20 mi away. The decreased weight of the beam shells allowed all 12 beams to be transported on two trucks, resulting in less congestion on the narrow, winding roads of rural Missouri.

The weight of the HC beams used on this project was about 3,100 pounds each empty. Filling the compression arch added about 6,800 pounds. The total weight of 9,900 pounds each is about 40 percent less than traditional steel beams.

Figure 24 shows a cross section of the beams, including the location of the compression arch formed by injection of the self-consolidating concrete.

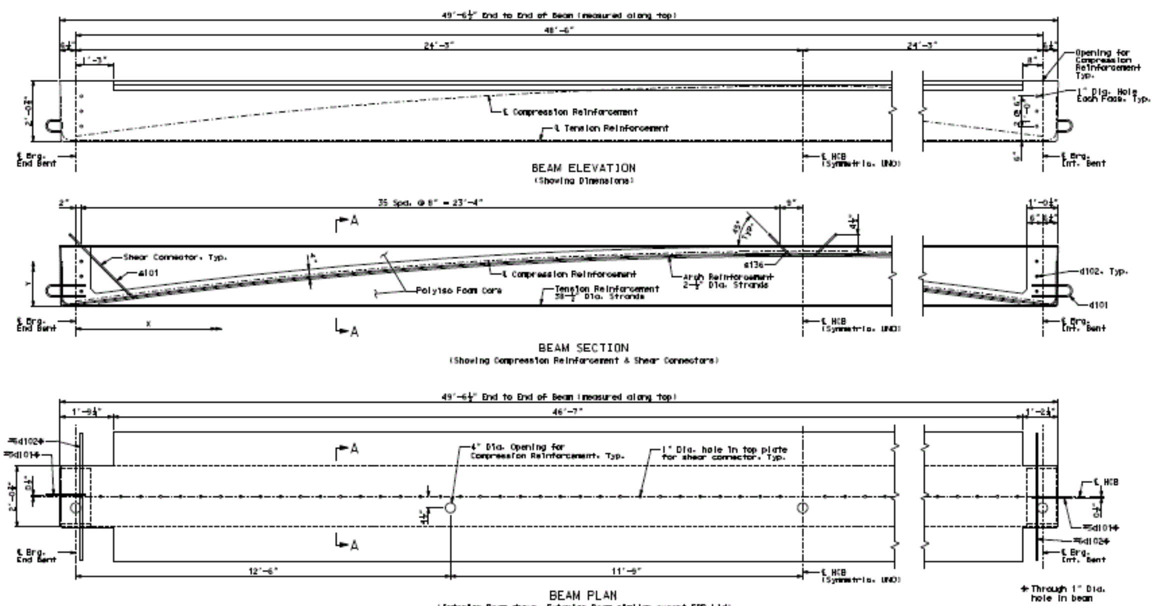

Figure 24. Cross section of HCB for Reynolds County structure.

SUBSTRUCTURE CONSTRUCTION

The existing substructure was determined to be inadequate for the proposed widened structure. Figure 25 shows the configuration of the new steel pipe piers that were placed. The number of spans was reduced from three to two.

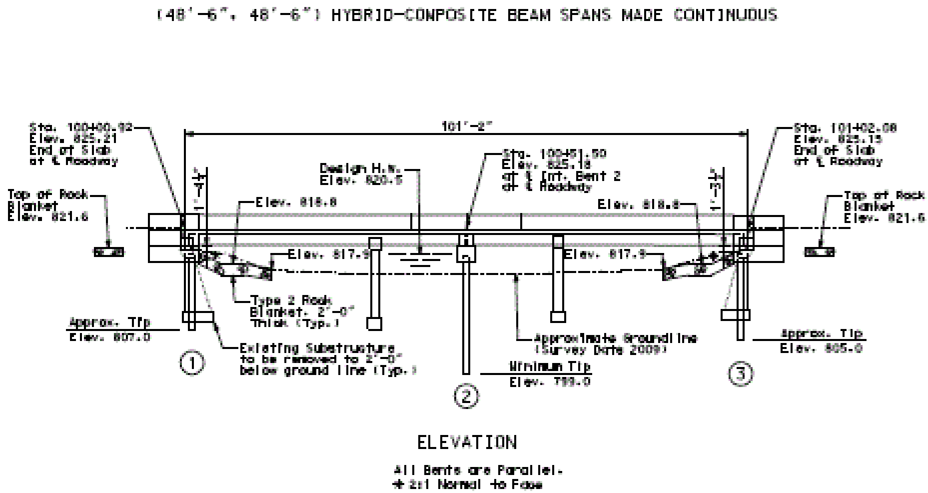

Figure 25. Plan view showing existing and revised pier locations for the Reynolds County structure.

SUPERSTRUCTURE CONSTRUCTION

The deck replacement consisted of the placement of six HCBs spaced on 4-ft, 4-in centers for each span. The beams were 48 ft, 6 in long and 2 ft, 5/8 in deep. On top of the beams was placed a traditional 8.5-in PCC deck with an overall (out to out) width of 26 ft, 8 in, providing a 24-ft roadway width. Figure 26 illustrates the cross sectional dimensions of the new structure.

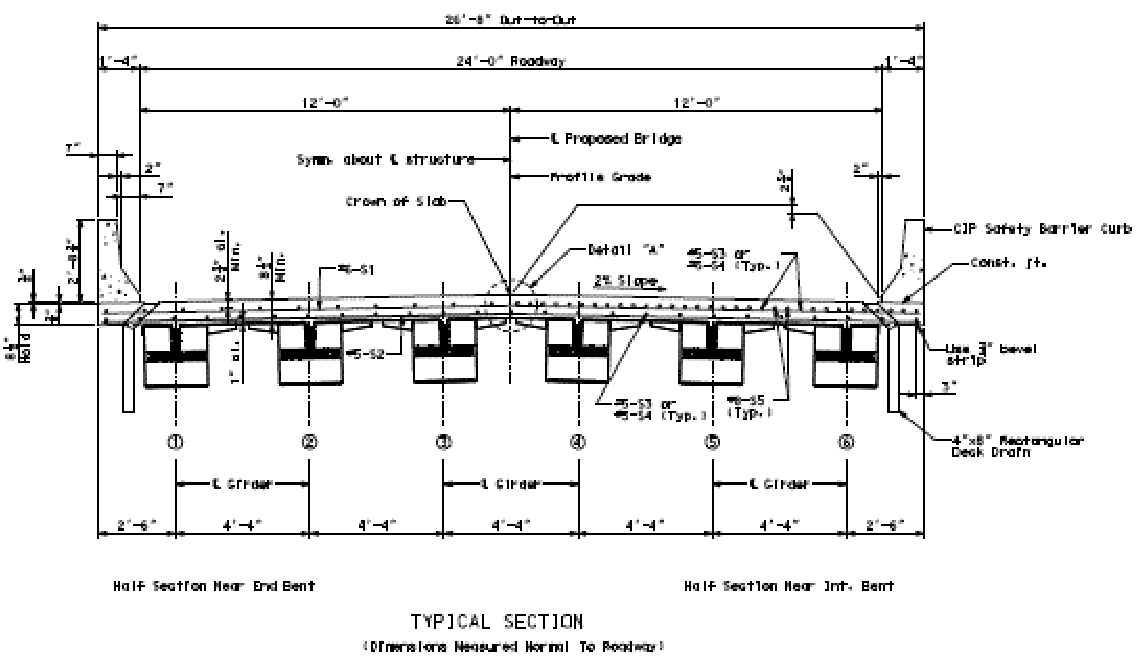

Figure 26. Cross section of HCB on Reynolds County location.

Tests were performed on self-consolidating concrete to ensure the mix would flow adequately through forms without forming voids. The slump test was modified in that the cone was inverted and the diameter of the resulting circle of mix was measured (see figure 27). The target diameter was between 30 and 32 in.

Figure 28 shows a second test run with the inverted cone set inside a basket with vertical bars to measure the ability of the mix to flow around obstacles.

Figure 27. Modified slump test.

Figure 28. Cage test performed at the Reynolds County site.

All beams were stockpiled alongside the project for insertion of the shear steel (see figure 29). The lightweight nature of the beams made setting them in place a relatively simple task. Figure 30 shows the beams moved into position using a small track hoe. A slightly larger crane was used to set the beams (see figures 31 and 32) where additional reach was required.

Figure 29. Beams at staging location after insertion of shear steel.

Figure 30. Beams moved to construction site using track hoe. (Photo courtesy of MoDOT)

Figure 31. First beams lifted into place over Ottery Creek Overflow. (Photo courtesy of MoDOT)


Figure 32. Begin beam placement on second span at Reynolds County site. (Photo courtesy of MoDOT)

Figure 33. Original 4-in access holes for concrete introduction.

Figure 33 shows how concrete was introduced at quarter points along the beam through 4-in holes. The concrete required substantial vibration to flow into the beam opening. The opening in the beam was expanded with a reciprocating saw with a wood blade so that the hose end would fit completely into the beam. This resulted in much easier flow and eliminated the need for most of the vibration. Figure 34 shows the self-consolidating concrete being pumped into place.

Figure 34. Self-consolidating concrete is pumped into place. Note removal of paving rail bars to allow increased flow around shear steel.

Figure 35 shows that, after the concrete set, there was a gap between the beams of about 1 in that required closing before the deck was poured. The fiberglass shell allowed a wooden two-by-four to be placed under the deck and screwed in place with drywall screws to provide the required form.

Figure 35. Gap between beam flanges.

DATA ACQUISITION AND ANALYSIS

As for the Douglas County project, project data were analyzed to provide the HfL program with sufficient information to support the use of HCB technology in future applications. The results of these analyses are presented in the following subsections.

For the sake of conciseness, explanations of the HfL goals are not repeated here. For details, please see the chapter on the Douglas County project.

SAFETY

Safety goals for HfL projects are based on worker safety during construction and traveler safety during and after project completion. The worker safety goal is set at a 4.0 or less, as reported on the OSHA 300 form available from the contractor. The public safety goal is a crash rate equal to or less than the preconstruction crash rate.

No worker injuries were reported on this project.

Even though the road was completely closed to all but local traffic, there was still one work zone crash, when a vehicle drove past two sets of signs and around two barricades and ran into the rear of a parked trailer. This crash was considered more of a traffic violation incident than a work zone safety issue.

The crash rates for each leg of the detour before and during construction are shown in tables 6 and 7.

Table 6. Crash rates for original and detour routes before construction, Reynolds County project.

Route	**Termini**	**Preconstruction**					**3-Year Rate**	**3-Year Rate (Facility Type)**	**3-Year Rate (Statewide by Route Designation)**
		Length (miles_	**Volume (3-year average)**	**Crashes (3-Year Totals)**					
				Fatal	**Injury**	**PDO**			
MO 49	Original Route MO 32 to Route. J	20.156	393	1	16	14	357.39	189.17	234.98
	(Detour Routes)								
MO 32	MO 49 West to Route KK	2.29	2,558	0	13	8	327.39	189.17	234.98
Route KK	MO 32 South to Route J	7.373	2,350	0	6	4	52.71	189.17	227.31
Route J	Route KK Southeast to MO 49	11.63	551	1	2	4	99.76	189.17	227.31

Table 7. Crash rates for original and detour routes during construction, Reynolds County project.

Route	Termini	Closure 6/11/2012 to 8/9/2012 (59 days)					Closure Rate	3-Year Rate Before Construction
		Length (miles)	Assumed Volume	Crashes				
				Fatal	Injury	PDO		
MO 49	MO 32 to Route J	20.156	N.A.	0	0	1	N.A.	189.17
MO 32	MO 49 West to Route KK	2.29	2,951	0	0	0	0	327.39
Route KK	MO 32 South to Route J	7.373	2,743	0	0	0	0	52.71
Route J	Route KK Southeast to MO 49	11.63	944	0	0	0	0	99.76

No crashes were reported on any of the detour routes, so all segments achieved the desired goal of a crash rate less than or equal to the rate before construction. No traffic volume data were collected on the original segment because it was open only to local traffic. Therefore, it was impossible to calculate a rate for the closure with the single work zone crash.

CONSTRUCTION CONGESTION

The standard HfL goal for impact of construction on the public is a 50 percent reduction compared to conventional methods. Historically, MoDOT has averaged between 90 and 100 days to replace a bridge of similar size on a similar roadway. However, with the MoDOT's Safe and Sound rapid bridge replacement program, the average closure duration was 42 days. Full roadway closure was used as the MOT strategy on about 96 percent of the bridge projects under this project.

The closure on this replacement was 59 days. Construction of this bridge off the existing alignment resulted in minimal disruption to the public. While this did not meet the HfL goal of a 50 percent reduction in construction time, it is substantially shorter than the average.

QUALITY

As noted in the chapter on the Douglas County project, HCBs offer several quality advantages, as well as a possible environmental benefit.

USER SATISFACTION

Although MoDOT received some negative comments on the duration of the road closure, any dissatisfaction was unrelated to the HCB technology.

ECONOMIC ANALYSIS

CONSTRUCTION COSTS

The original design for this structure using prestressed concrete beams resulted in an estimated cost of $231 per square foot. This amounts to an estimated total cost of $1,122,276 for HCB and $623,187 for prestressed concrete beams. Modification to use the HCB technology resulted in a final cost of about $416 per square foot, which is an increase of about 80 percent.

For this structure, the additional construction costs with the use of HCB were $475,639. This cost differential included the HCB cost of $228,800, a design cost of $73,905, a construction engineering cost of $19,045, a delivery charge of $16,000, and a mobilization cost of $29,222, for a total of $366,972. The redesign and the addition of the deck components, coupled with a credit for the unused beams, resulted in a change order with a total additional charge of $108,667.

LIFE CYCLE COSTS

The baseline scenario called for prestressed concrete beams to be placed side to side with an AC wearing surface (with a membrane) applied directly to the beam flanges. This was not considered a viable option for the HCBs. Because of this, the redesign included the addition of a traditional concrete deck. This redesign influenced the design and size of the HCBs because of the increased weight of the deck.

A life cycle cost analysis was performed to capture the cost impact of the differences in performance between an AC wearing course and a concrete deck. The expected service life of an AC wearing course was 7 years. The rehabilitation of AC wearing course would involve mill and overlay every 7 years at an estimated cost of $38.5 per square yard (including $13.5 and $25 per square yard of milling and overlay, respectively). At the end of 28 years, the AC wearing course would need a complete removal and reapplication of membrane. The estimated cost of complete removal and replacement was $80 per square yard (including $55 per square yard of membrane reapplication and $25 per square yard of overlay). With the as-built case, the traditional concrete deck involved 15 percent of half-sole repair at $50 per square yard and a seal at $4 per square yard. The estimated life cycle costs for both baseline and as-built cases are in table 8.

Rehabilitation of asphalt overlays or deck repair would not require full roadway closure detours.

Flagger operations would be adequate for MOT on prevailing low-volume traffic conditions with no significant delays anticipated during future bridge deck repairs, so future road user costs were not considered in the life cycle cost analysis.

The estimated life cycle costs were discounted to the present values using a long-term 30-year discount rate of 3.0. The period chosen for this analysis was 45 years. Appropriate salvage values were applied at the end of 45 years for both cases. Both the discounted values and the net present value are in table 8.

Table 8. Life cycle cost analysis of bridge deck for the Reynolds County project.

Year	Description	Baseline—AC wearing course with membrane		As-built—PCC deck	
		Undiscounted Costs	Discounted Costs	Undiscounted Costs	Discounted Costs
7	AC mill and overlay	$11,540	$9,383		
14	AC mill and overlay	$11,540	$7,629		
21	AC mill and overlay	$11,540	$6,203		
28	AC remove and replace	$11,540	$5,044		
30	PCC 15% half-sole repair			$20,413	$8,410
35	AC mill and overlay	$11,540	$4,101		
42	AC mill and overlay	$11,540	$3,335		
45	Salvage	-$6,595	-$1,744	-$10,207	-$2,699
Net Present Value			$33,951		$5,711
Difference in future costs		**$28,241**			

DETOUR/USER COST

Figure 22 illustrates the normal route and main assumed alternative route for the project. Table 9 illustrates both the traffic volumes (AADT, vpd) and distances of travel required using the primary and the alternative routes. The low traffic volumes on the alternative routes implied that the effect of traffic diverting to those routes would be negligible. Consequently, the only travel impact would be the additional travel time required by those diverting from the primary route to the alternative route. The posted speed limit on the facility was 55 mi/h. Inspection indicated that the typical operating speed was about 50 mi/h.

Table 9. Volumes and travel distances of primary and alternative routes for the Reynolds County project.

Route	Primary Route		Alternative Route		Increased Travel Distance on Alternative Route (mi)
	AADT (vpd)	Distance (mi)	AADT (vpd)	Distance (mi)	
MO 49	382	20.2	500-2,600	21.3	1.1

Assuming an average unit cost of $0.82 per mile for commercial vehicles (light and heavy trucks)[2] and $0.33 per mile for an average sedan[3] for the VOC (including costs for fuel, maintenance and repair, tires, and depreciation) and given the AADT of 684 vehicles with assumed 16 percent trucks for this project,[4] the following VOC is computed:

<u>As-Built Case</u>

VOC $_{Auto}$ = 382 (AADT) * 0.84 (percent autos) * 1.1 (mi) * $0.33 (per mi) * 59 (days)
= $6,875

VOC $_{Truck}$ = 384 (AADT) * 0.16 (percent trucks) * 1.1 (mi) * $0.82 (per mi) * 59 (days)
= $3,246

VOC $_{Total}$ = $6,875+ $3,246
= **$10,121**

<u>Baseline Case</u>

The VOC for the baseline case was not computed because under MoDOT's Safe and Sound rapid bridge replacement program, it would have taken almost the same amount of time to replace this bridge. No significant savings in the construction duration or VOC were expected. Therefore, the VOC cost differential between the baseline and as-built case was not considered in the economic analysis.

TRAVEL TIME COMPARISON RESULTS

Table 10 presents the results of the travel time analysis for the Reynolds County project. Overall, the mobility impact of the full road closure was minimal. Travel time increased only about 1.3 minutes per vehicle. Summed over all of the traffic diverting each day, the detour resulted in 8.3 vehicle-hours of additional travel time per day of closure.

Table 10. Mobility impact of full road closures for the Reynolds County project.

Route	AADT Diverting (vpd)	Increased Travel Distance (mi)	Increased Travel Time per Vehicle (min)	Daily Increase in Travel Time (vehicle-hours)
MO 49	382	1.1	1.3	8.3

The MoDOT *Engineering Policy Guide* estimates the cost to the public at $10.30 an hour per

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[2] Barnes and Langworthy, *The Per-Mile Costs of Operating Automobiles and Trucks*, 2003, Report No. MN/RC 2003-19, Minnesota Department of Transportation. Adjusted for fuel price increase and inflation in 2011.

[3] American Automobile Association, *Your Driving Costs 2012*. Both operating costs and per mile depreciation costs were considered. http://newsroom.aaa.com/wp-content/uploads/2012/04/YourDrivingCosts2012.pdf.

[4] MODOT 2011 Traffic Volume and Commercial Vehicle Count Map, Southeast District. http://www.mo-dot.org/safety/documents/2011_Traffic_SE-District.pdf.

private vehicle and $22.70 an hour per single and multiple–unit commercial truck.[5]

As-Built Case

Delay $_{Auto}$ = 382 (AADT) * 0.84 (percent autos) * 8.3 (veh-hr)* $10.30 (per hr) * 59 (days)
= $4,237

Delay $_{Truck}$ = 382 (AADT) * 0.16 (percent trucks) * 8.3 (veh-hr)* $22.70 (per hr) * 59 (days)
= $1,779

Delay $_{Total}$ = $4,237 + $1,779
= $6,016

Baseline Case

The travel delay costs for the baseline case were not computed because under MoDOT's Safe and Sound rapid bridge replacement program, it would have taken almost the same amount of time to replace this bridge. No significant savings in the construction duration or travel delay costs were expected. Therefore, the cost differential between the baseline and as-built case was not considered in the economic analysis.

SAFETY

As noted earlier, only one crash was reported during construction. The nature of the crash event was not related to work zone safety concerns, so it was not considered for safety analysis.

COST SUMMARY

The use of HCB in this project resulted in an increased construction cost of $475,639. The use of a PCC deck was required with HCB, while the AC overlay of the beam flanges would have been the conventional choice with prestressed box beams. While resulting in higher initial cost, the PCC deck is expected to have lower future maintenance costs than the AC overlay, resulting in net cost savings of $28,241 (net present value) over a 45-year analysis period. To summarize, the use of HCB in this project resulted in a net cost increase of $447,398, or 71.8 percent of estimated baseline costs.

[5] *Engineering Policy Guide*, Section 616.13 Work Zone Capacity, Queue and Travel Delay, WZ Impact Analysis Spreadsheet with HCM 2010 Program Directions, 2011. http://epg.modot.org/index.php?title=616.13_Work_Zone_Capacity%2C_Queue_and_Travel_Delay.

PROJECT DETAILS—MO 97 in DADE COUNTY

BACKGROUND

The third of the three structures replaced under this demonstration project was a bridge over Sons Creek on MO 97 in Dade County. The original structure consisted of a 95-ft-long, single-span steel I-beam structure 20 ft, 11 in wide built in 1935. At this location, MO 97 is a rural two-lane facility serving about 684 vehicles per day. This project was constructed on a new alignment just west of the existing structure. There was no closure of the roadway for the majority of the construction. However, the road was closed for 18 days while the new pavement was tied into the existing roadway. Figure 36 shows the detour route. The detour of about 12 mi is an increase of about 8 mi over the direct route length. Figure 37 shows the project site.

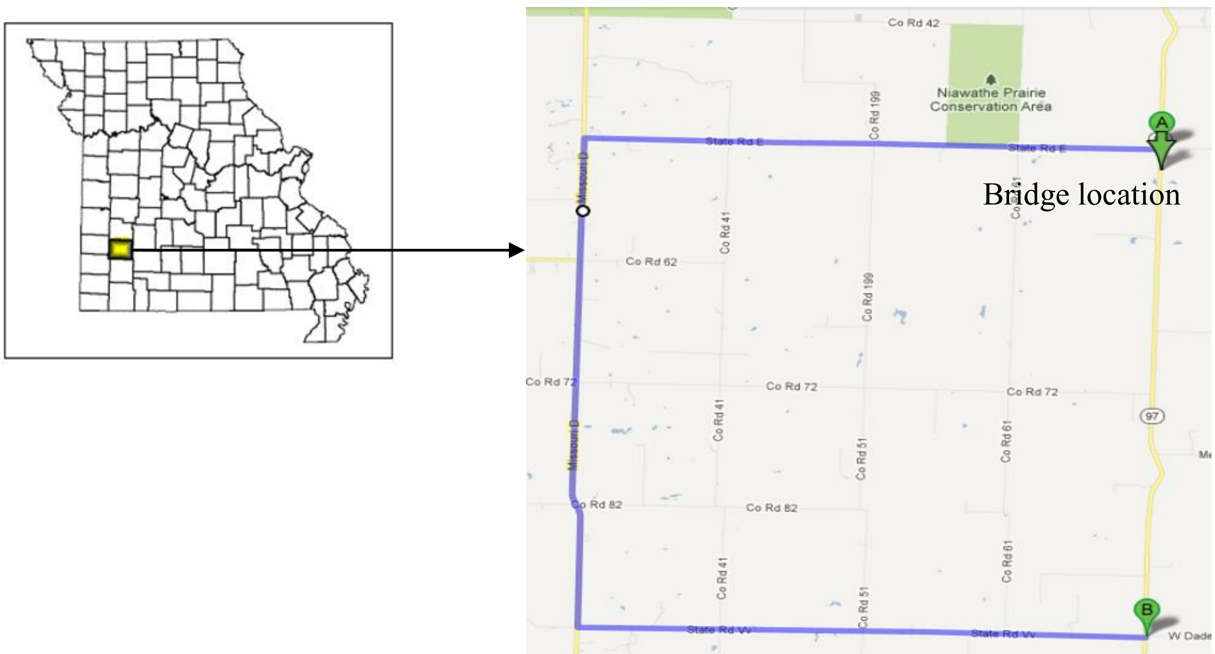

Figure 36. Dade County project location, with detour route highlighted in yellow.

Figure 37. Existing structure on MO 97 over Sons Creek in Dade County.

The new structure consists of a single 104-ft span that is 30 ft, 8 in wide, providing a 28-ft roadway on new alignment. The single span consists of three hybrid-composite box beams, each 105 ft, 7 in long and 5 ft high, with a width of 5 ft, 6 in. Construction took from May 21 to August 25, 2012, a total of 103 days.

PREFABRICATED BRIDGE COMPONENTS AND MATERIALS

Traditional construction for a structure of this size and type would be either steel I-beam or prestressed concrete I-girders. The weight of the HCBs used on this project was about 18,000 pounds each empty. Filling the compression arch added about 42,000 pounds. The total weight of 60,000 pounds each is about 40 percent less than traditional concrete box beams. Beams for this job were among the longest HCBs constructed to date and the first of the box beam variety. Concerns about the ability to fill these on sites without creating voids in the concrete arch resulted in the beams being filled at a plant in Indiana. The size of the beams required each of the three beams to be transported on individual trailers.

Figure 38 shows a cross section of the beams, including the location of the compression arch formed by injection of the self-consolidating concrete.

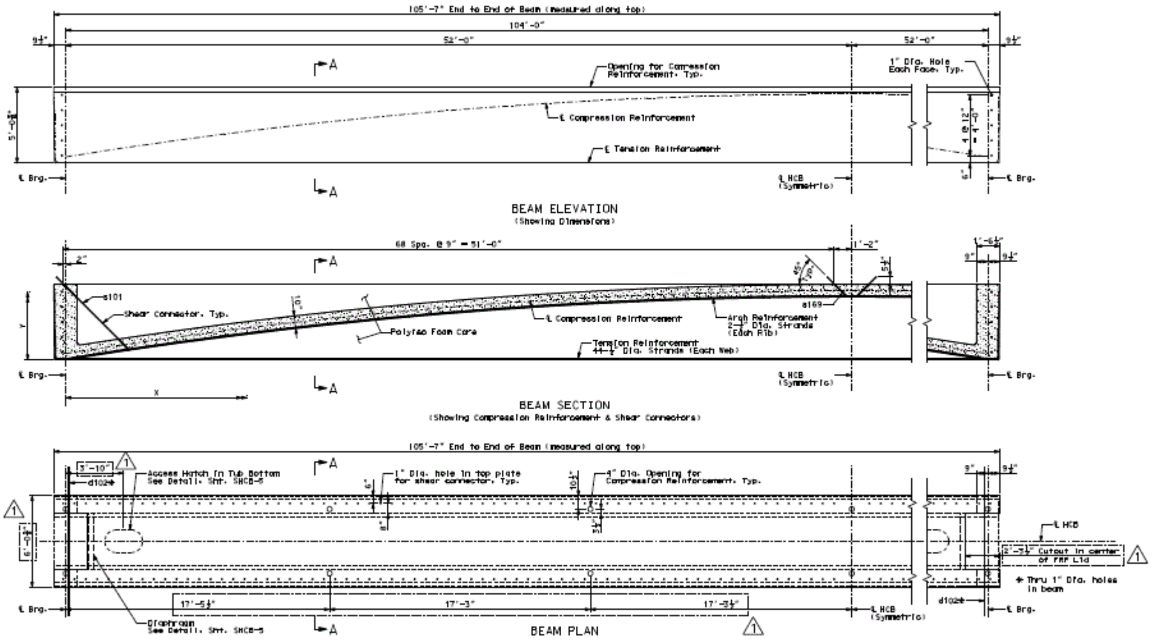

Figure 38. Cross section of HCB for the Dade County structure.

Figure 39 shows the end view cross section of the voided box beam section with the location of shear connectors, compression reinforcement, and foam.

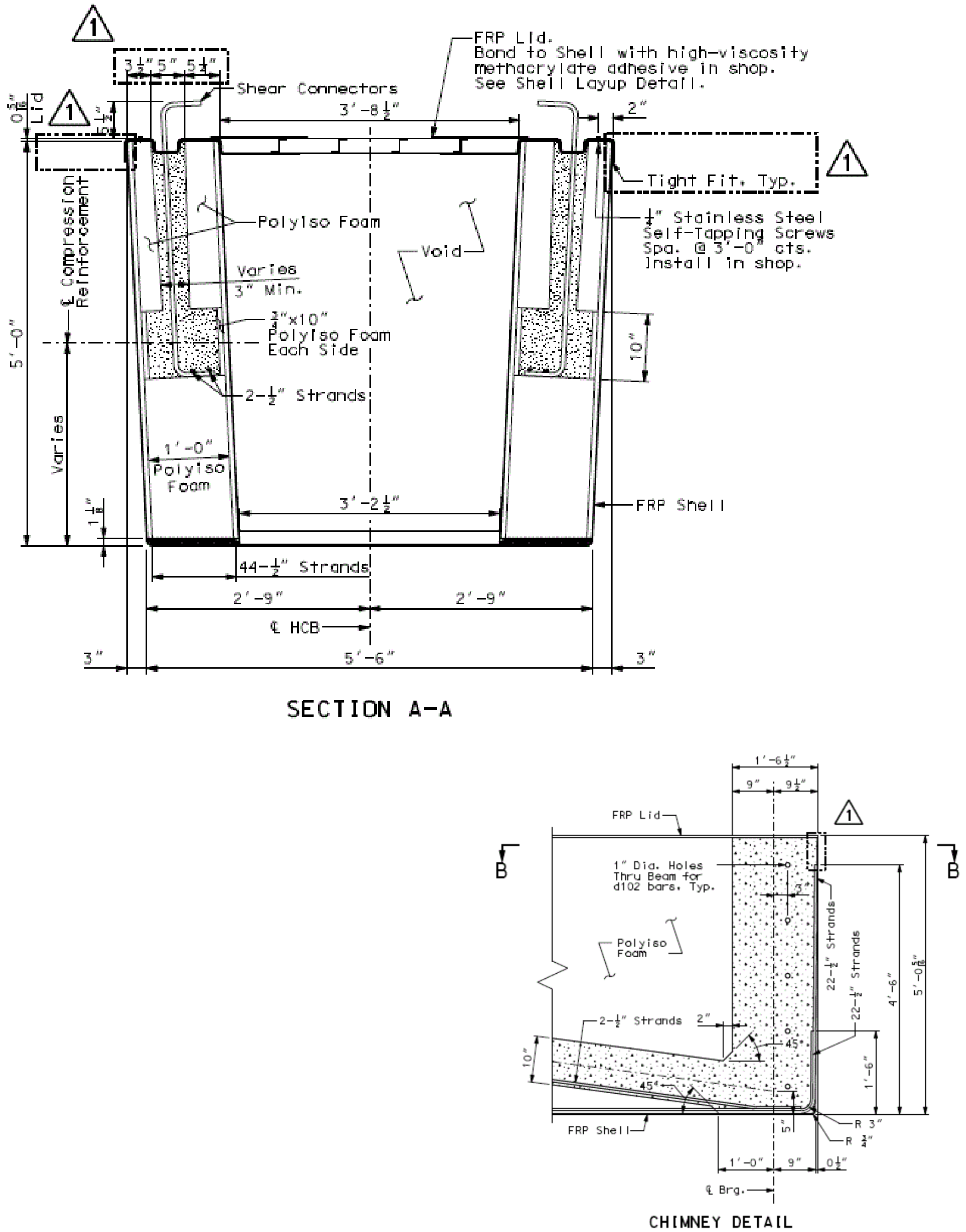

Figure 39. End view cross sections of hybrid-composite box beams showing location of compression arch.

SUBSTRUCTURE CONSTRUCTION

Figure 40 shows the abutment detail of the bridge constructed for this project. As noted earlier, the new bridge was constructed just west of the existing structure.

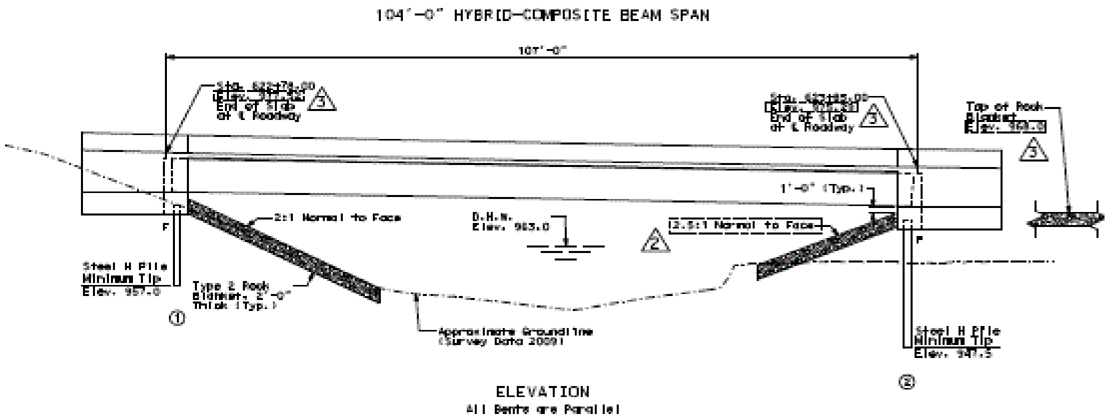

Figure 40. Abutment detail of the Dade County project.

SUPERSTRUCTURE CONSTRUCTION

The superstructure consisted of the placement of three HCBs spaced on 10-ft, 4-in centers. The beams were 105 ft, 7 in long, 5 ft high, and 5 ft, 6 in wide. On top of the beams was placed a traditional 8.5-in PCC deck with an overall (out to out) width of 30 ft, 8 in, providing a 28-ft roadway (see figure 41). The original deck measured 20 ft, 11 in wide, including a roadway width of 20 ft.

Because of the length and overall size of the beams, a temporary construction road was built next to the structure to allow them to be lifted into place by two cranes located at each end of the structure.

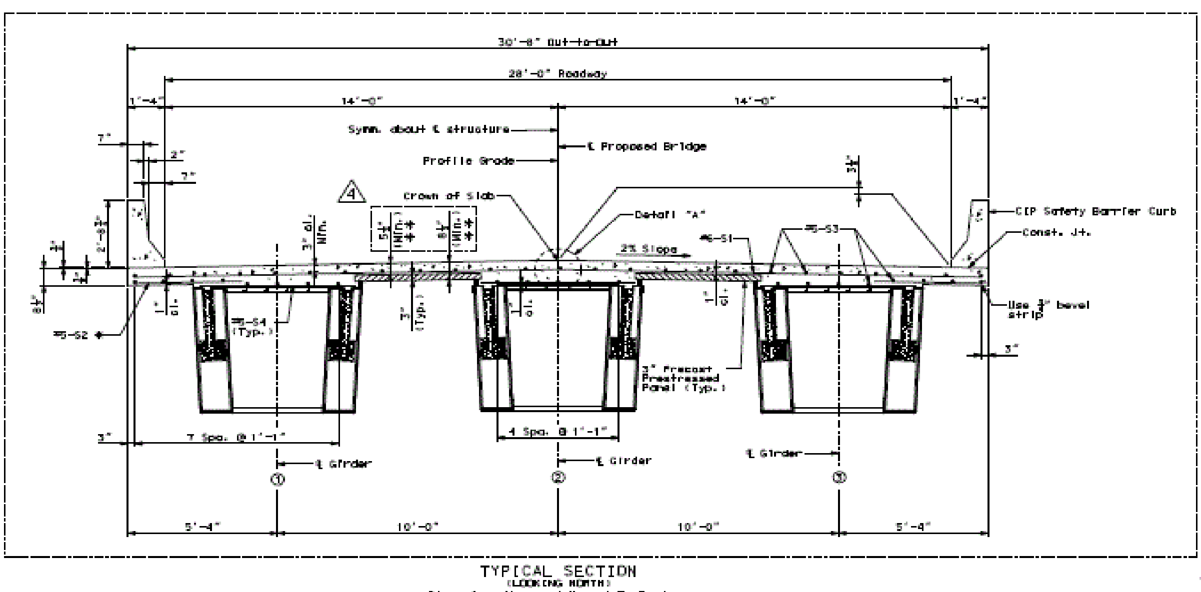

Figure 41. Cross section of hybrid-composite box beams for the Dade County location.

Figure 42. Beams lined up for installation.


Figure 43. Beams are prepared for lifting into place. Note pipe bolted into place to accommodate lifting straps.

Figure 44. First beam attached to cranes for placement.

Figure 45. First beam moved into place.

Figure 46. Deck placement on MO 97, Dade County.

Figure 47. Completed deck on MO 97, Dade County.

DATA ACQUISITION AND ANALYSIS

As noted for the Douglas County project, project data were analyzed to provide the HfL program with sufficient information to support the use of HCB technology in future applications. The results of these analyses are presented in the following subsections. For the sake of conciseness, explanations of the HfL goals are not repeated here. For details, see the chapter on the Douglas County project.

SAFETY

Safety goals for HfL projects are based on worker safety during construction and traveler safety during construction and in the future after project completion. The worker safety goal is set at a 4.0 or less based on the OSHA 300 form available from the contractor. The public goal is a crash rate equal to or less than the preconstruction crash rate.

No worker injuries were reported on this project.

For this report, a 3-year crash rate for each leg of the detour was compared to the rate calculated during the construction period, with the assumption that 100 percent of the traffic was diverted to the detour routes. Therefore, the preconstruction AADT of 649 was added to each leg of the detour route to calculate the crash rates during the closure period.

The crash rates for each leg of the detour before and during construction are shown in tables 11 and 12.

Table 11. Crash rates for original and detour routes before construction of the Dade County project.

Route	Termini	Length (miles)	Preconstruction				3-Year Rate	3-Year Rate (Facility Type)	3-Year Rate (Statewide by Route. Designation)
			Volume (3-year average)	Crashes (3-Year Totals)					
				Fatal	Injury	PDO			
MO 97	Route E West to Route E	4.055	649	0	2	3	173.50	189.17	234.98
Route E	MO 97 West to Route D	4.014	350	0	0	0	0.00	189.17	227.31
Route D	Route E South to Route VV	4.05	345	0	1	1	130.72	189.17	227.31
Route VV	Route E East to MO 97	3.949	148	0	0	0	0.00	189.17	227.31

Table 12. Crash rates for original and detour routes during construction of the Dade County project.

Route	Termini	Closure 8/7/2012 to 8/25/2012 (18 days)					Closure Rate	Closure Rate	3-Year Rate Before Construction
		Length (miles)	Volume (3-year average)	Crashes					
				Fatal	Injury	PDO			
MO 97	Route E West to Route E	4.055	N.A.	0	0	0	0	0	173.50
Route E	MO 97 West to Route D	4.014	999	0	0	0	0	0	0.00
Route D	Route E South to Route VV	4.05	994	0	0	0	0	0	130.72
Route VV	Route E East to MO 97	3.949	797	0	0	0	0	0	0.00

Table 12 shows there were no crashes reported on the detour routes during construction, resulting in a rate of zero, meeting the HfL goal.

CONSTRUCTION CONGESTION

The standard HfL goal for impact of construction on the public is a 50 percent reduction compared to conventional methods. Historically, MoDOT has averaged between 90 and 100 days to replace a bridge of similar size on a similar roadway. However, with MoDOT's Safe and Sound rapid bridge replacement program, the average closure duration was 42 days. Full roadway closure was used as the MOT strategy on about 96 percent of the bridge projects under this project.

On this project, the actual roadway closure amounted to only 18 days. Construction of this bridge off the existing alignment resulted in minimal disruption to the public.

QUALITY

The main measure of quality for the HCBs is expected to be the inherent corrosion resistance of the fiberglass shell, resulting in a very low maintenance bridge that will not rust, crack, or spall like conventional concrete beams or require painting like a steel beam. The service life of the HCB is expected to be in the range of 75 to 100 years.

Another impact of the HCB technology was the change to a PCC deck rather than the AC overlay of the beam flanges that would have been used with PC box beams. While having a higher initial cost, it is expected to result in lower future maintenance costs.

An environmental benefit is also possible if large-scale use of the technology becomes common. The volume of concrete used in a HCB is about 80 percent less than a prestressed concrete girder. Given that the production of PCC is one of the largest contributors to the carbon footprint of the construction industry, a shift to this type construction could have a positive impact.

USER SATISFACTION

MoDOT did not conduct a satisfaction survey as a part of this project. However, as with all Safe and Sound bridge projects, extensive preconstruction public involvement and education efforts were carried out. This was especially true in the case of closures where significant detours were required. While MoDOT received some negative comments on the duration of the closure, the delay had nothing to do with the HCB technology.

ECONOMIC ANALYSIS

In addition to promoting improvements in safety, construction-related congestion, and quality, the value of the innovations is also important. This can be done by comparing the cost of the HfL technology to the cost of a project constructed using traditional methods. Bridge replacements of this size would traditionally be either steel I-girder or prestressed concrete I beam construction.

CONSTRUCTION COSTS

The original design for this structure using prestressed concrete beams resulted in an estimated cost of $170 per square foot. This amounts to an estimated total cost of $988,693 for HCB and $542,187 for prestressed concrete beams. Modification to use the HCB technology resulted in a final cost of about $310 per square foot, an increase of about 80 percent.

For this structure, the additional construction costs with the use of HCB were $436,699. This cost differential included the HCB cost of $265,191, a design cost of $76,210, a construction engineering cost of $33,080, a delivery charge of $40,906, and a mobilization cost of $29,222, for a total of $444,609. The redesign and the addition of the deck components, coupled with a credit for the unused beams, resulted in a total change order credit of $7,910.

LIFE CYCLE COSTS

The baseline scenario called for prestressed concrete beams to be placed side to side with an AC wearing surface (with a membrane) applied directly to the beam flanges. This was not considered a viable option for the HCBs. Because of this, the redesign included the addition of a traditional concrete deck. This redesign influenced the design and size of the HCBs because of the increased weight associated with the deck.

A life cycle cost analysis was performed to capture the cost impact of the differences in performance between an AC wearing course and a concrete deck. The expected service life of an AC wearing course was 7 years. The rehabilitation of an AC wearing course would involve mill and overlay every 7 years at an estimated cost of $38.5 per square yard (including $13.5 and $25 per square yard of milling and overlay, respectively). At the end of 28 years, the AC wearing course would need a complete removal and reapplication of membrane. The estimated cost of complete removal and replacement was $80 per square yard (including $55 per square yard of membrane reapplication and $25 per square yard of overlay). With the as-built case, the traditional concrete deck involved 15 percent of half-sole repair at $50 per square yard and a seal at $4 per square yard. The estimated life cycle costs for both baseline and as-built cases are in table 13.

Rehabilitation of asphalt overlays or deck repair would not require full roadway closure detours. Flagger operations would be adequate for MOT of traffic on prevailing low-volume traffic conditions with no significant delays anticipated during future bridge deck repairs, so future road user costs were not considered for life cycle cost analysis. The estimated life cycle costs were discounted to the present values using a long-term 30-year discount rate of 3.0. The period chosen for this analysis was 45 years. Appropriate salvage values were applied at the end of 45 years for both cases. Both the discounted values and the net present value are in table 13.

Table 13. Life cycle cost analysis of bridge deck for the Dade County project.

Year	Description	Baseline—AC wearing course with membrane		As-built—PCC deck	
		Undiscounted Costs	Discounted Costs	Undiscounted Costs	Discounted Costs
7	AC mill and overlay	$13,643	$11,093		
14	AC mill and overlay	$13,643	$9,020		
21	AC mill and overlay	$13,643	$7,334		
28	AC remove and replace	$13,643	$5,963		
30	PCC 15% half-sole repair			$24,133	$9,942
35	AC mill and overlay	$13,643	$4,848		
42	AC mill and overlay	$13,643	$3,942		
45	Salvage	-$7,796	-$2,062	-$12,066	-$3,191
Net Present Value			$40,139		$6,752
Difference in future costs		**$33,387**			

DETOUR/USER COST

Figure 36 illustrates the normal route and main assumed alternative route for the project. Table 14 illustrates both the traffic volumes (AADT, vpd) and distances of travel required using the primary and alternative routes. The low traffic volumes on the alternative routes implied that the effect of traffic diverting to those routes would be negligible. Consequently, the only travel impact would the additional travel time required by those diverting from the primary route to the alternative route. The posted speed limit on the facility was 55 mi/h. Inspection indicated that the typical operating speed was about 50 mi/h.

Table 14. Volumes and travel distances of primary and alternative routes for the Dade County project.

Route	Primary Route		Alternative Route		Increased Travel Distance on Alternative Route (mi)
	AADT (vpd)	Distance (mi)	AADT (vpd)	Distance (mi)	
MO 97	609	4.1	150-350	12.1	8.0

Assuming an average unit cost of $0.82 per mile for commercial vehicles (light and heavy trucks) and $0.33 per mile for an average sedan for the VOC (including costs for fuel, maintenance and repair, tires, and depreciation) and given the AADT of 684 vehicles with assumed 14.8 percent trucks for this project,[6] the following VOC is computed:

[6] MODOT 2011 Traffic Volume and Commercial Vehicle Count Map, Southwest District http://www.mo-dot.org/safety/documents/2011_Traffic_SW-District.pdf

As-Built Case

VOC $_{Auto}$ = 684 (AADT) * 0.852 (percent autos) * 8 (mi) * $0.33 (per mi) * 18 (days)
= $24,663

VOC $_{Truck}$ = 684 (AADT) * 0.148 (percent trucks) * 8 (mi) * $0.82 (per mi) * 18 (days)
= $10,627

VOC $_{Total}$ = $803,677+ $129,849
= **$35,290**

The VOC for the baseline case was not computed because under MoDOT's Safe and Sound rapid bridge replacement program, it would have taken almost the same amount of time to replace this bridge. No significant savings in the construction duration or VOC were expected. Therefore, the VOC cost differential between the baseline and as-built case was not considered in the economic analysis.

TRAVEL TIME COMPARISON RESULTS

An assumption of a 50 mi/h operating speed implies a unit travel time of 1.2 minutes per mile. This unit travel time can be applied to the increased travel distances for each alternative route compared to the primary route to estimate the mobility impact of the full road closures on a per-vehicle basis. Multiplication by the primary route AADT provides a per-day impact measure. The results of this analysis are in table 15. Overall, the mobility impact of the full road closure was minimal. Travel time increased only about 9.6 minutes per vehicle. Summed over all of the traffic diverting each day, the detour resulted in 97.4 vehicle-hours of additional travel time per day of closure.

Table 15. Mobility impacts of full road closures on the Dade County project.

Route	AADT Diverting (vpd)	Increased Travel Distance (mi)	Increased Travel Time per Vehicle (min)	Daily Increase in Travel Time (vehicle-hours)
MO 97	609	8.0	9.6	97.4

While the normal traffic study was conducted, there was actually no cost differential for the use of HCBs in the construction. The time to complete the construction was considered the same as required for the original design of prestressed concrete beams.

The MoDOT *Engineering Policy Guide* estimates the cost to the public at $10.30 an hour per private vehicle and $22.70 an hour per single and multiple–unit commercial truck.[7]

[7] *Engineering Policy Guide*, Section 616.13 Work Zone Capacity, Queue and Travel Delay, WZ Impact Analysis Spreadsheet with HCM 2010 Program Directions, 2011. http://epg.modot.org/index.php?title=616.13_Work_Zone_Capacity%2C_Queue_and_Travel_Delay

As-Built Case

$\text{Delay}_{\text{Auto}}$ = 684 (AADT) * 0.852 (percent autos) * 97.4 (veh-hr)* $10.30 (per hr) * 18 (days)
= $15,385

$\text{Delay}_{\text{Truck}}$ = 684 (AADT) * 0.148 (percent trucks) * 97.4 (veh-hr)* $22.70 (per hr) * 18 (days)
= $5,890

$\text{Delay}_{\text{Total}}$ = $15,385 + $5,890
= $21,275

The travel delay cost for the baseline case was not computed because under MoDOT's Safe and Sound rapid bridge replacement program, it would have taken almost the same amount of time to replace this bridge. No significant savings in the construction duration or the travel delay costs were expected. Therefore, the cost differential between the baseline and as-built case was not considered in the economic analysis.

SAFETY

As shown in table 12, no crashes were reported on any of the affected routes during the construction period. Furthermore, since the designated detour for this project carries lower volumes of traffic, it is assumed that the project has no significant safety impact on the detour routes.

COST SUMMARY

The use of HCB over prestressed beams resulted in an increased cost of $436,699 for construction. The use of PCC deck was required with HCB, while the AC overlay of the beam flanges would have been the conventional choice with prestressed box beams. While resulting in higher initial cost, the PCC deck is expected to have lower future maintenance costs over the AC overlay, and resulting in net future cost savings of $33,387 (net present value) over a 45-year analysis period. To summarize, the use of HCB in this project resulted in a net cost increase of $403,312, or 74.4 percent of estimated baseline costs.

OVERALL CONCLUSIONS AND LESSONS LEARNED

The MoDOT experience with HCB construction was a positive one, but the HCBs were more expensive than conventional prestressed concrete beams.

The constructability was considered good. The beams were easy to ship because of their light weight. Even those filled before delivery were substantially lighter than an equivalent beam of steel or concrete. While one of the anticipated benefits of this light weight was that the beams could be set with smaller cranes, in the MoDOT experience, this advantage was negated because a large crane was already on the job for driving pile.

The use of precast panels to form the deck on the HCBs caused no issues. Standard neoprene bearing pads were also used with no problems noted.

One of the contractors was required to provide a maintenance and inspection guide for the HCBs that should prove helpful in the future. Another contractor is conducting a study, "Field Evaluation of Hybrid Composite Bridges in Missouri," which is scheduled to be completed in June 2013. This report will contain details of deflection measurements taken over time on the in-place structures as well as the infrared video used for void detection in filling the beams.

The camber designed into the beams did not perform as would be expected on conventional beam designs. For example, beams for the structure in Douglas County were delivered to the plant site and filled before delivery to the job. The 60-ft beams were cast on the ground with the haunch elevations set with blocking. The deflections were less than designed, but they caused no real issues.

The structure in Reynolds County was constructed as originally planned (i.e., the beams were set empty and filled in place). The camber in these 50-ft beams was not sufficient, and deflection eliminated all camber once the beams were filled.

Beams for the Dade County location were filled in Indiana before delivery. At 104 ft long and 5 ft deep, these beams were by far the longest and deepest sections used. These beams did not deflect at all, causing issues with deck thickness. This was further complicated by the fact that the structure was built on a sag vertical curve.

Workers noted that the HCBs involved more preparation work. The bars in the end of the beams that tie them together laterally must be inserted, as does the entire top shear steel. This is a time-consuming process, but this time could be reduced with experience.

While the light weight of the beams is an overall advantage, there were some unexpected issues. Traditional methods of attaching forms for the side wall pour had to be modified to prevent the beams from tipping over. In fact, steel posts had to be attached to the end abutments to attach safety lines, as the weight of a man falling with a safety line could cause the beams to rotate.

There was a general level of discomfort about the ability to fill the compression sections completely, even using self-consolidating concrete. Care must be taken to adjust the mix with the appropriate additives to ensure a mix that flows easily and does not set up in transit to the jobsite.

A different contractor was used on each of the structures, so experience gained from previous trials was limited to the MoDOT bridge and research staff. The contractor and staff at the concrete plants never gained a comfort level with the product. Experience with the mockup pour for Douglas County showed that it is important to have the holes spaced at shorter intervals than previously planned and that to ensure adequate head pressure the holes must be at least as large as the pump hose.

The large box beams filled in Indiana were examined using an infrared camera. Several voids were detected and repaired before shipment.

Construction duration and user impacts were similar for HCB and prestressed concrete beams. Full roadway closure was used as the preferred MOT strategy in about 96 percent of the MoDOT Safe and Sound bridge replacement program.

The economic analyses indicated that HCBs were more expensive than prestressed concrete beams on both an initial and life cycle cost basis. Using HCBs increased the initial cost of the beams from 30 to 80 percent on the three projects. This increase is due in part to the cost of transporting the beams from the factory in Maine, a haul distance of more than 1,400 mi. Also, unlike prestressed concrete beams, the AC overlay of the beam flanges is not a feasible choice for HCB. While the use of PCC decks with HCB added to the initial costs, this cost increase was somewhat offset through savings in future costs because of low maintenance requirements. The net increase in life cycle costs ranged from 23 to 74 percent on these three projects.

It is expected that the experience gained from this project will allow for more routine use of this technology in the future, if a more cost-effective source for the product becomes available.

In general, the concept of the HCB appears sound, and the overall use may be limited only by the availability of the beams at a regional or local level.