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Deployment Support and Caltrans' Implementation of the Sealzall Machine

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LIST OF ACRONYMS AND ABBREVIATIONS

AC	Asphalt Concrete or Alternating Current
AHMCT	Advanced Highway Maintenance and Construction Technology
BearCat	BearCat Manufacturing Incorporated
Caltrans	California Department of Transportation
Center Lane Miles	The total length of a given road from its starting point to its end point
CFM	Cubic Feet per Minute
Cimline	Cimline Pavement Maintenance Group – Plymouth Industries Inc.
COZEEP	Construction Zone Enhanced Enforcement Program
Crafco	Crafco Incorporated an Ergon Company
DC	Direct Current
Detack	A biodegradable liquid that eliminates sealant tack when directly sprayed onto freshly applied hot pour sealant
EB	Eastbound
FHWA	Federal Highway Administration
GMC	General Motor Corporation
GUI	Graphical User Interface
Hwy	Highway
IMMS	Caltrans Integrated Maintenance Management System
I/O	Input(s) and Output(s)
L	Liter
MAZEPP	Maintenance Zone Enhanced Enforcement Program
MPH	Miles per Hour
NB	Northbound
OE	Operating Expenses
Overband	Sealant applied to pavement surface adjacent to crack
PCC	Portland Concrete Cement
PLC	Programmable Logic Controller
Post Marker	Designates a physical location on the highway
PreCise	Data logger
PSI	Pounds per Square Inch
SB	Southbound
Service Life	Total period an asset remains in use, or ready to be used, in a productive process
Spall	Break in a concrete pavement slab resulting in a void
TMA	Truck Mounted Attenuator
USD	United States Dollars
V	Volts
WB	Westbound
Wono	Caltrans abbreviation for Work Order Number

ABSTRACT

The Advanced Highway Maintenance and Construction Technology (AHMCT) Research Center, in partnership with the California Department of Transportation (Caltrans) have successfully completed a multi-year research effort to develop the Sealzall prototype high production crack sealing machine. The goal of the project was to provide Caltrans maintenance with original equipment, which could dramatically increase highway sealing production rates as well as radically improving worker safety on the highway. The Sealzall prototype has successfully completed a one year field trial operated by Caltrans' District 11 maintenance crews sealing longitudinal pavement cracks on various highways, across a wide range of environments district wide. The Sealzall sealant kettle heat-up and sealing systems are fully automated and can be monitored and controlled from inside the truck's cab. The longitudinal sealing operation requires only a single operator who controls the entire sealing operation while driving the truck at a continuous 2-5 mph in a moving lane closure. Caltrans workers are not on foot or exposed to direct highway traffic while on the highway. Using the Sealzall, Caltrans has consistently sealed 5-8 linear miles of edge joints a day, and the Sealzall machine can be utilized to yield up to \$4.0 million dollars in cost savings annually as described in the Sealzall cost benefit analysis contained in this report. The Sealzall machine can also be used to seal in-lane and random pavement cracks with a traditional manual sealing operation in a stationary lane closure. The current status of the Sealzall machine is described in detail in this report along with various potential strategies which could be utilized to further development of this equipment and continue deployment with Caltrans maintenance crews.

EXECUTIVE SUMMARY

The Advanced Highway Maintenance and Construction Technology (AHMCT) Research Center, in partnership with the California Department of Transportation (Caltrans) have successfully completed a multi-year research effort to develop the Sealzall prototype high production crack sealing machine. The goal of the project was to provide Caltrans maintenance operations with innovative new equipment that dramatically increases joint sealing production rates and radically improves worker safety on the highway. The Sealzall prototype has successfully completed a one year field trial operated by Caltrans' District 11 maintenance crews to seal longitudinal pavement edge joints on various highways, across a wide range of environments district wide. The Sealzall sealant kettle heat-up and sealing systems are fully automated and can be monitored and controlled from inside the truck's cab. The longitudinal sealing operation only requires a single operator who runs the entire sealing operation while driving the truck at a continuous 2-5 mph. Caltrans workers are not on foot or exposed to direct highway traffic while on the highway. System configuration and sealant kettle reloading tasks are conducted at nearby safe areas off the highway. Longitudinal sealing operations are normally conducted in moving closures either from the shoulder of the highway adjacent to live lanes, or in a rolling in-lane closure. COZEEP and MAZEEP support is typically utilized, especially when rolling ramp closures are necessary. An integrated Sealzall exclusive no-tack spray system prevents following traffic from tracking-up the fresh sealant. With the Sealzall, Caltrans has consistently sealed 5-8 linear miles of longitudinal edge joints a day compared to 1 mile for the traditional manual operation. This increase in production rate affords Caltrans the capability of sealing their full inventory of longitudinal joint cracks at a calculated annual cost savings of \$4.0 million dollars. The Sealzall machine can also be quickly configured for traditional manual in-lane and random crack sealing operations in a standard stationary temporary lane closure work zone. A hand application wand, which is front bumper mounted, provides the driver a close up view of the sealing and enables the Sealzall to be operated in the lane closure in the same direction as traffic. A high capacity air compressor is also integrated on the Sealzall to provide a high pressure air blast for crack cleaning. A record of Sealzall production rates has been compiled based on AHMCT experience riding along during the operations and on Caltrans IMMS records. A detailed cost analysis has been developed which compares the Sealzall field trial data to current standard Caltrans manual crack sealing operations. The current status of the

Sealzall machine is also described in detail, and various potential strategies to continue deployment of this equipment in Caltrans maintenance operations are presented. A supplementary section describes in detail effective and efficient crack cleaning techniques, which dramatically extend the effective life of hot applied longitudinal joint seals.

AUTOMATED CRACK SEALING PROGRAM

The Sealzall is the latest and most ambitious project to date in a series of automated crack sealing equipment deployment research projects developed by the Advanced Highway Maintenance and Construction Technology (AHMCT) Research Center, in partnership with the California Department of Transportation (Caltrans). The basic goal of the previous development projects was to design an automated longitudinal-only pavement crack sealing machine that reduced sealing costs and improved worker safety. Since studies have shown that up to 80% of the surface water that enters a pavement gets in through the lane shoulder joint [1], the sealing of longitudinal joints is of the upmost importance. For the Sealzall project, the design goal was to expand machine functionality to include the ability to seal all types of pavement cracks on the highway. To accomplish this, a single heated sealant passage, hose and universal wand assembly had to be developed to accommodate both automated longitudinal and manual in-lane sealing operations. This dual functionality together with the new feature of sealant hose recirculation necessitated a far higher level of machine control complexity. Consequently, to ensure that the machine is not overly complicated to operate, the Sealzall had to be designed with a considerably higher level of automation than past longitudinal only sealing machines had possessed.

Previous longitudinal-only crack sealing machine designs were all based on the procedure of adding sealant supply blocks to the kettle during the sealing process at approximately an equal rate of sealant application. This has always been the standard operational procedure recommended by all the sealant kettle manufacturers for melting efficiency. Since the longitudinal machine sealing operation is continuous, it was necessary to have workers ride in the truck bed with a supply of sealant blocks and slide them into the trailered kettle as the machine applied sealant at constant 2-5 mph in the work zone. A Caltrans policy was later reinforced which prohibits workers from riding in a moving vehicle. This safety mandated rule had effectively invalidated the basic operating mode of the Caltrans built double kettle trailer longitudinal machine, which had been deployed at the time because continually stopping to add sealant blocks is impracticable. From that point forward, the longitudinal sealing operation was run continuous and the double kettles drained. This approach still provided seal production gains, but limited the sealing distance to the available kettle capacity. This practice also significantly lengthened kettle recovery times due in part to the reduction of internal heating surfaces caused by an empty kettle.

The Sealzall project was the first machine designed specifically to operate while emptying the kettle, which represents a major shift in the operational objective. Not adding sealant blocks favors the application process, but limits range. The Sealzall was initially designed to be operated in conjunction with a secondary kettle with high-speed transfer capabilities as the means to substantially extend sealing distance.

SEALZALL BASIC DESCRIPTION

The Sealzall sealant application system prototype (Figure 1) is a completely self-contained automated accessory mounted to a GMC C550 chassis. A rear mounted 2.4L auxiliary gasoline engine is the main power source for the Sealzall system and only shares the fuel tank and battery connection with the truck. The automated machine can be quickly configured to seal both longitudinal cracks and manual in-lane cracks.



Figure 1. Sealzall Machine Platform

The longitudinal sealing process is an automated continuous rolling operation, which is controlled from inside the truck's cab, while in-lane cracks are sealed in the traditional manual method. A chassis mounted 400 gallon BearCat propane fired sealant kettle dispenses hot-applied polymer modified asphalt sealer (Crafco) by means of an electrically heated hose and wand assembly mounted to the front of the truck in a bumper basket. Underneath this basket is a laterally driven carriage mechanism that holds and positions the sealant wand for longitudinal sealing operation.

System operational control is automated to simplify operator training and improve operational efficiency. An in-cab touch screen GUI display (Figure 2) provides a simple operator interface to the PLC unit, which directly and automatically controls all the necessary onboard sealing and support systems. Starting the auxiliary engine starts the Sealzall system and activates the user control GUI screen in the cab. The Sealzall machine has a fully automated heat-up cycle process, which reduces the complex series of steps required to heat the system down to a single a push of a button on the GUI screen. The Sealzall heat up process takes about an hour and a half for all necessary systems and the sealant to reach operational temperature before transitioning

into the recirculation phase. The operator then mounts the sealant wand in the recirculation cradle on either side of the truck and with another push of a button on the GUI, the hot sealant is circulated through the entire sealant passage and back into the kettle. The Sealzall is then ready to be configured and begin sealing. Sealant blocks are loaded into the kettle through 2 hatches on top of the unit. The Sealzall can also be loaded by means of high speed hot sealant transfer from a separate transfer trailer kettle for an extra sealant production boost.



Figure 2. Operator GUI Touchscreen

Sealzall Development

The Sealzall machine was designed and primarily built at AHMCT utilizing the GMC dual steer chassis from a previous generation machine. Conventional sealing systems needed to be redesigned to accommodate the extended level of automation required to meet the expanded set of design goals. Great effort was taken to minimize the application of sensors and controls and to maximize robustness on the highway. Basic functional testing was completed in the laboratory to ensure that all systems were functioning as designed. An initial user program was written and laboratory tested to verify basic automated functionality. All possible development was completed prior to the introduction of sealant into the kettle.

Once sealant was introduced, any further operational testing and development would need to be conducted on the highway. The nature of conventional polymer modified sealants limits their viability in the kettle at pour temperature to approximately eight hours before becoming permanently coked. In addition, the 400 gallon BearCat kettle needs to be half full to cover the heating surfaces. Therefore, when testing with hot sealant, it is necessary to identify a location suitable for pouring a large quantity of sealant within a few hours of heating. Therefore, the best situation for machine testing is to be on the highway at a location where the sealant can be applied so as to prevent dumping large quantities of hot sealant. This issue complicated the Sealzall initial testing phase but was the only plausible method to gain the hot sealant operational time necessary to fully develop the automated control and user interface programs.

SEALZALL INITIAL HIGHWAY TESTING

Sealzall initial testing was initially conducted on Caltrans District 4 highways and then completed on District 11 region highways. At first, AHMCT operated the Sealzall with Caltrans providing the sealant and traffic control. Functionality was added to the basic automated control program each successive day of sealing. Hardware upgrades, additional sensors, and controls were integrated onto the Sealzall between operations as necessary.

The development of the Auto Heat function was the most time consuming task. Since there is only one start-up heating cycle per day to experiment with the hardware and program functionally, it took several sealing operations to determine the necessary settings and then test them. The testing phase was beneficial to Caltrans maintenance since in the progress, AHMCT sealed many miles of joint cracks on the highway.

The Sealzall was originally built with copper tubing sealant passages between the kettle and sealant hose. The copper joints began to deteriorate and had to be replaced with steel pipe. However, the biggest challenge of the initial testing phase was finding clean longitudinal crack to seal. Though it was beyond the scope of this research project, far more time was devoted to experimenting with aggressive crack cleaning methods than was spent sealing the clean cracks. Eventually, the effort to identify an efficient crack cleaning attachment to the Sealzall was abandoned and all further seal testing was limited to areas with existing clean cracks such as in locations where AC shoulders had been recently replaced.

GENERIC SEALZALL LONGITUDINAL JOINT SEALING OPERATION

Generally when the dedicated operator enters the yard in the morning, the operator starts the Sealzall, and with a press of the **AUTO** button on the GUI screen, the auto heat cycle is initiated. Approximately an hour later, the kettle is warm enough to open the hatches and add sealant blocks. At approximately 1-1/2 hours into the heating process, the user screen will indicate that the sealant hose and passage are warmed sufficiently to begin recirculation. The operator presses the **RECIRCULATION** mode button on the GUI screen, connects the wand to the recirculation cradle and closes the retaining guard. A green light indicates the wand is secure and the operator presses the seal button on the wand to start the auto recirculation process. Sealant blocks are added to top off the kettle.

The Sealzall automatically cycles the sealant pump forward and reverse to establish hot sealant flow through the sealant wand. When the user screen indicates recirculation is occurring, the Sealzall is ready to be transported to the work site. Recirculation flow through the sealant hose continues during transport guaranteeing seal flow through the wand at the worksite. The Sealzall can be heated and ready to leave the yard in as soon as two hours. The **TRANSPORT** button is pressed on the GUI screen for safety when leaving the yard, which pauses the propane burner for the drive out to the work site. Upon reaching the work zone, the **RESUME** button is pressed on the GUI screen, which restarts the burner to recover the heat lost during transport. Typically, it takes about 30 minutes of reheating for the kettle to reach sealant application temperature. During this time, the machine is configured for the sealing process in a safe location off the highway adjacent to the day's sealing start point.

The Sealzall can be operated from the shoulder, or in the lane, depending on work site specifics and operator preference. The in-lane moving operation is generally preferred by Caltrans crews because the shoulder is not consistent. Starting the in-lane longitudinal sealing operation involves the trailing traffic control measures to take the lane. When the lane clears, the Sealzall pulls out and lines-up the sealing shoe with the joint. Then the operator presses a control button on the handheld wireless controller and the sealing shoe drops down straddling the joint crack. Pressing the control button again starts sealant flow and when a sealant puddle forms in the shoe, the operator guides the sealant puddle along the joint filling the crack and creating a uniform overband.

The operator has full control of all sealing systems from inside the cab. The operator can select to engage the detack spray when sealing across ramps to ensure that trailing vehicles do not track-up the fresh sealant. When the kettle sealant level approaches half capacity, the operation pulls off the highway to reload. Typically, the trailing traffic control vehicles are loaded with pallets of sealant. These trucks pull up alongside of the Sealzall kettle and the sealant blocks are simply tossed in to refill the kettle. The BearCat kettle was selected for use with the Sealzall because it has all of its heating surfaces in the lower half of the kettle. Unlike standard double boiler kettles, the BearCat kettle can run efficiently while half empty and consequently exhibits unusually fast reheat times. The refilled kettle requires approximately 30 minutes to be reheated while the crew takes a break. This refill process is typically repeated 2 to 3 more times a day. After leaving the highway, the crew breaks for a late lunch before returning

to the maintenance station. Therefore, a typical sealing operation is out on the highway for approximately four hours and covers on average six miles of longitudinal joint crack and typically applies about three standard pallets of boxed sealant per operation.

To terminate the sealing operation, the sealing shoe is lifted and the Sealzall machine is driven to a safe location off of the highway. On the GUI screen, the **SHUT DOWN** button is pressed, which automatically prepares and shuts down the Sealzall. The sealing shoe is removed from the wand, and the hose is secured in the front bumper tray for transport back to the yard. The return trip is the most efficient time to refill the gasoline and propane tanks, especially if these fuels are not available in the maintenance yard. Upon returning to the yard, the kettle is reloaded with sealant blocks to make use of the latent heat in preparation for the next sealing operation.

CALTRANS DEDICATED OPERATOR TRAINING

By February 2012, the development of the automatic control programs had progressed to a point where it became prudent to train a dedicated Caltrans operator to run the machine in highway maintenance operations. Training began March 1, 2012 and training consisted of showing the operator the auto heating cycle in operation and then having the operator run the longitudinal sealing operation on Highway 86 under AHMCT supervision. The first training day, five miles of longitudinal crack were sealed in a moving lane closure. The next day the dedicated operator ran the operation with AHMCT adopting more of an observer role and answering questions. From that point forward, Caltrans ran the highway sealing operations entirely. AHMCT merely provided support and collected information, which enabled the control program to be enhanced to correspond with the preferences of the Caltrans operator for both the longitudinal and random sealing processes. In addition to the programming changes, the longitudinal sealing shoe was modified to improve its controllability, smoothness and longevity. These changes involved experimenting with the silicon rubber shape and thickness along with the shape of the shoe walls. Periodically throughout the year of deployment, modifications to the automated heating cycle settings were made primarily to compensate for different temperatures and environmental factors, which have a great influence on the kettle auto heating performance.

SEALZALL DEPLOYMENT TRIAL

The Sealzall was turned over to Caltrans District 11 Desert Maintenance Crews for use in March 2012. The Sealzall primary configuration was complete, and a dedicated operator had been trained who would travel with and operate the Sealzall throughout District 11. The operator, with his many years of highway operations and traffic control experience, quickly became the de facto authority on creating sealing work plans and running the Sealzall on the highway. The dedicated operator would travel to the local yard and determine the operational specifics including how the machine would travel in the lanes or shoulder, the required resources, traffic control and closure configuration, if and when to add sealant blocks, and when to call in temporary MAZEPP ramp closures.

In the year of trial deployment in District 11, the Sealzall has consistently recorded dramatic longitudinal production increases, which are presented in the following list of District 11 Sealzall sealing jobs and supported by Caltrans IMMS records. Other unique Sealzall benefits, such as improving worker safety, reducing traffic impact and permitting access to work zones on the highway are presented in the Sealzall cost benefit analysis section later in this report.

Highway 86 (Salton Sea) IMMS Wono #2696339

The first Sealzall trial work site was on Highway 86 and is shown in Figures 3, 4 and 5. Sealing occurred on the edge and center cracks northbound (NB) and southbound (SB) in the section south from the Riverside County line post mile 58 to 69, a total of 44 lane miles. The #1 and #2 in-lane PCC cracks and joints were recently sealed with polymer concrete. It was only necessary to seal the joints between the PCC lanes and both shoulders with polymer modified sealant (Crafco). These longitudinal cracks were blown clean when the in-lane cracks were cleaned and sealed. Therefore, longitudinal crack cleaning was not required before sealing.

The operation began March 6, 2013 by sealing the longitudinal crack along the shoulder while running the Sealzall and traffic control with both SB traffic lanes open. The moving closure consisted of two TMA trucks and a signboard truck all spaced apart and moving along the shoulder. Beginning with the Sealzall kettle full and sealing a small crack, the operation was able to seal five miles in about three hours. The Caltrans operator was instructed on-the-fly on how to operate the Sealzall and he performed all the day's sealing.

The Sealzall kettle holds approximately two pallets of sealant. The kettle was 90% full at the start, a pallet was added on the highway, and the day was finished with the kettle completely empty. So, approximately three pallets (or approximately 600 gallons) of sealant were applied the first day. Time on site was about four hours, of which at least half was static consisting of kettle heating time and lunch. Hence, five miles of longitudinal sealing occurred, dispensing 600 gallons of sealant in less than two hours with no traffic impact and no workers being exposed directly to traffic. At the time, this equipment operator had 14 years of highway maintenance experience in this area, and he estimated that their standard sealing operation could have sealed approximately half of a mile at that site. Accordingly, on his first day of training with the Sealzall, he increased his sealing production by ten times.



Figure 3. Longitudinal Sealing Highway Shoulder Joint Sealing Operation - Hwy 86

On the second day (March 7, 2012), the kettle was empty. Since sealant blocks encased in foam were being used (Figure 5), the kettle was unable to be completely refilled this day. Still, 4-1/2 miles were sealed and this involved pouring two pallets of sealant in the same four hour time period. On this occasion, the kettle was half filled in an attempt to improve the next day's melting performance. Foam blocks melt far slower than traditional boxed sealant, clog the loading hatches, and ultimately produce a poorer performing seal. Manufacturers have gotten away from packaging sealant in foam, but District 11 still had a stockpile of foam block sealant that had to be used up before new sealant could be purchased.

On the third day (March 8, 2012), by leaving the kettle half full and starting the kettle when the operator first arrived in the morning, the kettle's sealant was completely melted by the start of the day's sealing on the highway. From this point on, it was determined to try and keep

the kettle half full to enable the foam blocks to melt quicker. The day's melting production was a full three pallets, but since sections of this part of the crack were up to eight inches wide and three inches deep, the sealing operation covered only two miles of longitudinal crack.

The next week's goal was to complete the 11.6-mile section of longitudinal shoulder crack. On the fourth day (March 14, 2012), the Sealzall was operated in a moving closure in the #2 lane. While sealing the first ten miles of edge joint, the TMA trucks could not squeeze by the guardrails at many culverts along the highway without crossing over the sealant. As such, sealing was stopped a small distance short of each culvert. The Sealzall sealed these remaining short segments from the lane while speeding up between culverts to minimize traffic obstruction. The remaining 1.6 miles of the longitudinal crack was sealed at the end, completing the seal of the 11.6-mile section. On the fifth day (March 15, 2012), the Sealzall was operated from the shoulder again and driven over the entire length of the 11.6-mile section. The purpose was to seal any short sections of joint along the way that needed a recap in order to bring the seal surface flush with the highway. Typically, wider cracks always need a recap, but the majority of this joint was very narrow and a very small portion of the overall distance required the recap. AHMCT was not present for the remainder of this job.



Figure 4. No Tack Spray - Hwy 86

(Notice Foam Covered Sealant Blocks)



Figure 5. Loading Sealant Blocks - Hwy 86

Interstate 8 Ramp Sealing (Sidewinder) IMMS Wono #2703287

On March 9, 2012, the Sealzall was used to seal random AC cracks on the eastbound (EB) entry ramp at Sidewinder Road post mile 87-88 on Interstate 8 as shown in Figure 6. This was the first Sealzall manual in-lane sealing operation, so AHMCT quickly trained the dedicated operator how to operate the Sealzall in manual sealing mode. Almost a mile of merge lane and

some ramp was sealed with about 1-1/2 pallets of sealant in about 2-3 hours of work time. The Sealzall and crew returned later in March on the 26th, 27th and 29th without AHMCT present to complete the three remaining ramps at this location.

The Sealzall random sealing process and production rates are comparable to traditional sealing operations. The main advantage of the Sealzall manual random sealing operation is that the vehicle operates orientated forward in the same direction as traffic and backs in the lane. This configuration is more favorable than needing to turn the vehicle around and drive in the opposite direction of traffic, which is common for the standard trailered sealant kettle sealing operations.



Figure 6. Merge Lane Manual Sealing - Hwy 8

Interstate 8 Sealing (Descanso) IMMS Wonos #2770412, 2773087, 2774047

Caltrans independently operated the Sealzall June 1-8, 2012 to seal all longitudinal center and edge cracks on Interstate 8 in both the EB and westbound (WB) lanes between Willows Road in Alpine post mile 31.7 and Japatul Valley Road post mile 39.6. In this job, 32 lane miles of longitudinal crack were sealed in five days, which is an average of 6-1/2 miles a day. All the sealing was completed in moving lane closures. This was a new shoulder that needed sealing and required no crack cleaning.

Repair Sealzall-Kearny Mesa (June 26, 2012)

AHMCT scheduled a few days to service the Sealzall and address some non-critical repairs when the Sealzall was idle between sealing jobs. The truck and auxiliary engines were brought to an outside shop for regularly scheduled oil and filter service. During the Descanso job, the sealant level sensor had begun to read incorrectly. The sensor probe sheath appeared to be clogged from bits of unmelted sealant block foam. AHMCT made the needed Sealzall repairs

at the District 11 Kearny Mesa shop. The sealant level sensor was removed from the kettle and cleaned. The AC generator drive belt had been failing frequently, so the profile of the V-belt pulley was re-machined and a heat shield was installed in an attempt to extend the belt lifecycle. The repairs were completed over a couple of days work, and the Sealzall was returned to service.

Summer Downtime

The Sealzall sat idle in the District 11 Santee yard that summer. Maintenance crews were focusing on mowing operations, which were the mandated high priority that Summer to mitigate the wild fire hazard that had been a major problem in that area. The Maintenance supervisor in the Santee yard contacted AHMCT about using the machine a couple of times. AHMCT referred him to the District 11 people associated with the Sealzall to coordinate use between yards. However, the coordination was unsuccessful and the requested sealing work was not accommodated.

Escondido Repair (October 25-26, 2012)

After sitting all summer, the Sealzall auxiliary engine battery was dead, the GMC chassis needed a smog check, and the AC system need to be repaired. As such, AHMCT personnel flew down and completed the repairs.

Escondido Sealing IMMS Wonos #2876921, 2891556

This was a longitudinal sealing operation that ran from October 29 to November 13 on Interstate 15. The shoulder and center longitudinal joints were sealed in both the NB and SB lanes from mile marker 43 to 54, which is an 11 mile stretch between Father Serra Rd. and the Riverside County line. Interpretation of the IMMS records show that it took eight days to seal 44 lane miles, which calculates to an average of 5-1/2 miles a day. The Caltrans dedicated operator, reported that up to eight miles had been sealed in one of these days, but supporting data went unreported in the IMMS record.

Chula Vista Training IMMS Wonos #2942785, 2944169

On January 22-24, 2013, AHMCT personnel trained a new dedicated San Diego metro based operator for the Sealzall. The new operator was instructed by AHMCT as to how the Sealzall auto heating procedure operates and he observed the process in the yard. Then, the Sealzall went out to a moving longitudinal center crack sealing operation on Highway 905

starting from the Mexican border crossing. The new operator was given some quick instruction and started sealing north. The sealant flow rate was extremely slow and the new operator only sealed 1-2 miles that day.

On the second day, the original dedicated operator was there to help train the new operator. He was able to answer many production and traffic control questions about how previous, highly productive operations had been run. Unfortunately, this day's operation was equally as slow due to an uncharacteristically slow sealant flow rate. The sealant pump was worn out due to normal wear and was already due to be replaced. Since AHMCT had a replacement pump on site at the Caltrans Chula Vista yard, it was decided that the sealant pump would be replaced overnight in an attempt to solve the sealant flow problem for the next day's sealing operation.

The pump was successfully changed, but the next day's sealing flow was nearly as slow as before. The source of the problem was then determined to be caused by the old sealant blocks that were being added to the kettle. Once the sealant temperature settings were increased, the sealant flow rate improved, but the overall sealing production rate was significantly lower than normal. Since this supply of sealant was old and the blocks were covered in foam, the blocks took far longer to melt in the kettle than those used in the Escondido and Descanso jobs. During this operation, a random PLC problem occurred involving the burner cycling control. Once identified, resetting the system power solved the problem, but since this was a potential safety hazard, the control program had to be further developed to protect against this potential error.

The next day the sealing operation was rained out and this provided the opportunity to work with the Sealzall to develop the burner safety programming change. AHMCT was unable to complete the burner program update and get it running correctly in the remaining time that day. A return trip would be necessary the following week.

Chula Vista Support IMMS Wono #2957506

AHMCT personnel flew down February 4-7, 2013 and installed a working version of the burner safety program. Also, a sealing operation was used to provide additional training time to the new dedicated operator. During the sealing process, the PLC began to exhibit random problems similar to symptoms seen in overheating conditions, but the temperature was mild. A new PLC and analog modules were purchased overnight and installed for the following day's sealing operation.

The next day, the new PLC was installed and the Sealzall seemed to be operating normally. During that day's operation, about three miles of longitudinal crack were sealed on Highway 905, which seems to be the average production rate given the sealant blocks being used. The blocks were old and encased in foam; each of these factors taken separately slows the melting process, but when combined dramatically increases sealant block melt times.

Chula Vista Sealing IMMS Wono #2986704

The Chula Vista Caltrans crew operated the Sealzall independently for the first time February 8-15, 2013 and was unable to get sealant to flow through the sealant hose. It remains unknown what the source of the problem was, but the crew made several attempts to heat the kettle with no success. The successive cycles without refreshing sealant caused the sealant in the kettle to become severely coked. With the Sealzall project travel funds nearly depleted, the Sealzall would have to be returned to UC-Davis where an effort to save the kettle could best be attempted.

Sealzall Return Trip (February 25-27, 2013)

AHMCT flew down to District 11 and drove the Sealzall back to UC-Davis. The kettle was subsequently super-heated in a closely watched safe location in an attempt to melt and remove the coked sealant from the machine. This type of super-heating, above recommended sealant and heating transfer oil temperatures limits, is undesirable and could damage the system. The effort was ultimately successful requiring the kettle to be heated to 560°F, 60°F above normal operating temperature in order to melt the coked sealant. The Sealzall kettle was drained and scraped clean and was ready to be refilled again. The Sealzall then seemed to be operating normally again and was parked at UC-Davis awaiting a plan for future use.

Sealzall Current Status (As of End of Project – June 30, 2013)

The research and development of the prototype Sealzall machine has been completed. The machine was adopted by Caltrans District 11 maintenance crews and utilized throughout the area to seal a wide range of pavement cracks over the past year. During this deployment period, Caltrans has proven dramatic production, safety and efficiency gains by using the Sealzall in longitudinal sealing operations. Caltrans District 11 Maintenance has requested the return of the

Sealzall, but the Sealzall development project was at its end and project support funds had been exhausted.

TRANSFER TANK OPERATIONS

The transfer tank trailer has not been operated in conjunction with the Sealzall machine. Sealant melting rate remains the sole factor that limits Sealzall sealing production rates. Adding the Transfer kettle option to the Sealzall sealing operation would clearly alleviate the hot sealant limitation and in conjunction with moving closure operations, could provide substantial increase in the lane miles of sealing production. During the yearlong deployment phase, Caltrans District 11 maintenance crews were generally satisfied with the Sealzall sealing production rate utilizing the on-board 400 gallon BearCat kettle alone. Operating the Transfer Kettle trailer together with the Sealzall would increase crew size and operational complexity, which is not appealing for this level of operation.

A key issue that was identified in this deployment was that Sealzall production rates are greatly influenced by sealant block packaging and age. The sealing jobs, which used fresh sealant blocks loaded into the kettle without packaging, ran consistently and produced the highest production rates. When old sealant blocks packaged in foam were loaded into the Sealzall kettle, melting rate was dramatically reduced. These jobs using old foam covered blocks took 2-3 times longer to melt and drastically decreased sealing production rates. The ability to control the sealant blocks used in a Caltrans sealing job should be considered equally as important as the number or size of kettles utilized when contemplating the potential of achieving greater sealing production rates.

UNRESOLVED SEALZALL OPERATIONAL ISSUES

Several Sealzall operating issues have been identified as follows:

PLC Overheating - The Sealzall machine functions normally in mild ambient temperatures but is sensitive to temperature extremes. As the air temperature at the work site approaches 90° F, the Sealzall controller begins to reach its maximum temperature specification. This can lead to sporadic random controller errors and can sometimes cause a controller fault, which requires the system power to be cycled thus resetting the PLC. Several measures incorporated to mitigate the problem have been effective such that an active sealing operation can typically work through the fault problem should it occur on the highway. The lack of dependable PLC operation makes the training and operation more complicated and limits where and when the Sealzall is used.

Air Compressor Overheating - The high volume rotary screw compressor integrated onto the auxiliary engine has a very small operational temperature range. Compressor oil normally runs between 190-220° F. A safety switch shuts down the compressor when a maximum oil temperature of 230° F is reached. The air compressor is designed to run continuously and unload at maximum pressure. On the Sealzall, when the compressor is run continuously, it overheats and shuts down intermittently. The ambient temperature has a noticeable effect on the frequency, but the auxiliary engine compartment temperature also seems to be a major contributor to the problem. Mitigating efforts have had minimal effect, and measures recommended by the manufacturer have not been beneficial. Currently, the air compressor is configured to periodically cycle in order to maintain only the required system air pressure to operate the basic Sealzall sealing systems. The intended crack cleaning function using the air compressor has been abandoned until a solution to the overheating problem can be determined.

Auxiliary Engine Battery Circuit - The Sealzall auxiliary engine electrical system was designed to function independent of the truck chassis electrical system. In operation, after several hours of sealing, the auxiliary battery loses charge and the engine will not turnover, or start. The quick fix in the field was to connect the auxiliary and truck batteries together. The Sealzall has been operating without a problem in this configuration for several months and could continue, but this should be resolved in a more fundamental manner.

AC Generator Belt - There has been a persistent problem with AC generator drive belt failures.

A back-up plug-in power option was added to the Sealzall early on in the initial testing phase. Should the AC generator stop working, the operator can plug in an extension cord to a shop's power outlet to heat the sealant hose and passage. Once sealant hose recirculation flow is established during the auto heat-up process, the AC power is no longer needed for the day's sealing operation. Mitigation measures have reduced the belt failure issue, but only a redesign to a much larger drive belt would genuinely solve the problem.

PreCise Data Logger - Caltrans had requested that a PreCise data logger be attached to the Sealzall to aid in the collection of production numbers and track usage. It would be very useful for data inputs to collect when the Sealzall is in the process of applying sealant to the highway since the Sealzall in operation is continually pumping sealant and switches between recirculation through the bypass, or hose to the kettle, or applying sealant to the pavement. Therefore, to determine when sealant is being applied, logic has to be programmed into the PLC to identify the sealing process and toggle the last remaining free output on the PLC. The second available input to the PreCise unit would most likely identify if the sealing operation was longitudinal or in-lane, by reading the sealing shoe lift relay. The PreCise power would be connected to the chassis and the key power connected to the auxiliary engine ignition to record overall Sealzall running time. The programming of the PLC to output sealant application has been developed but not tested nor has any of the wiring or installation been attempted on the Sealzall.

FUTURE SEALZALL DEVELOPMENT

The research and development of the Sealzall machine prototype has been completed. The machine was adopted by Caltrans District 11 maintenance crews and utilized throughout the area to seal a wide range of pavement cracks. During this one year deployment period, Caltrans District 11 has established a proven record of dramatic production, safety and efficiency gains by using the Sealzall in longitudinal sealing operations. Predominantly District 11, but also District 4 Caltrans maintenance crews have requested access to the Sealzall for upcoming scheduled highway sealing operations. Caltrans must now determine the level of interest to continue Sealzall funding for support, development and research.

Should Caltrans be interested in pursuing Sealzall technology and integrating it into their highway maintenance operations, there are several opportunities available. The options range from redeploying the “as is” Sealzall, to the building of additional upgraded machines and many alternatives in between. When examining the different options, the method of support of the Sealzall when deployed to Caltrans Maintenance crews should be considered. Since the Sealzall has not been added to the Caltrans fleet and doesn't have an assigned asset number (equipment ID number), it is unlikely that Caltrans would provide vehicle service internally. Therefore, AHMCT has provided all Sealzall vehicle service and support at a cost which is covered by research and deployment funds.

Sealzall “As Is” Redeployment Option

To return the Sealzall to Caltrans service in District 11 with their operational experience would be the most basic option moving forward. The Sealzall prototype is currently fully operational, and the District 11 crews understand the machine's capabilities and limitations as described in the aforementioned section and could put the Sealzall to good use. It is recommended though, that at a minimum, the installation of the PreCise unit be completed on the Sealzall. Should the Sealzall deployment be continued in its current form without any significant changes or upgrades, it is unlikely any unique additional production or operational information would be generated. This basic option would also not provide the benefit to Caltrans' objective of acquiring additional units until the remaining deficiencies are resolved.

Resolve Deficiencies and Redeploy Sealzall Option

Of the remaining Sealzall operational issues, a few involve relatively minor modifications. Resolving the most critical minor deficiencies prior to return of the Sealzall back to Caltrans service in District 11 would be a prudent strategy. These enhancements would improve system reliability, benefit productivity, and simplify deployment support. This minimal effort could be small enough to be potentially supported under AHMCT Deployment Support funds.

- ***Solve AC generator belt failure issue and increase system voltage to 110VAC*** - The standard Cimline electrically heated hose used on the Sealzall is designed to operate at 70-80VAC. As per Cimline installation recommendations, the AC generator rotation speed was

slowed down to obtain the necessary voltage reduction. For the Sealzall, it has become apparent that a better approach would be to run the AC generator up to full speed generating 110VAC, which would improve sealant passage surface heater performance. The hose voltage would then be reduced with a voltage clipping circuit (dimmer). Running the AC generator at full speed will also improve generator cooling performance. Redesigning the AC generator drive system could mitigate both the continual 4L V-belt failure problem and also increase the AC generator up to the necessary speed with a larger width and diameter drive pulley system.

- ***Air compressor component cooling*** - Rotary screw air compressor overheating and thus tripping the safety shutdown switch has been an ongoing problem. Ambient temperature plays a significant role in determining run times between overheating events, but operation in relatively mild temperature does not fully prevent the overheating events from occurring. The problem persists after several mitigation attempts. The current theory as to the principal source of the problem may be the vertical orientation of the air compressor components. Testing and redesign would take a major effort, so instead another minor mitigation attempt could be tried to reduce the overheating problem. A heat shield could be installed in the burner galley between the rear side of the melter and the front side of the auxiliary engine enclosure. This is the hottest side of the kettle and it directs much of this heat towards the auxiliary engine enclosure a short distance away. For this reason there are not any ventilation holes in this side of the auxiliary engine enclosure. The addition of a heat deflector shield would allow for ventilation holes to be added to the galley side of the engine compartment. This should at least enable the air compressor to run continuously in mild temperature conditions.
- ***Electrical system random faults*** - There is an infrequent drop in 13 VDC power that resets the PLC and user screen. The system power returns quickly, but the operator needs to step through the user program to return to the prior location in the program. This usually occurs during the sealing process and results in a pause of less than a minute. The source of the problem is currently unknown, but it may be related to a loose electrical connection, or a faulty relay in the battery power circuit. To cover both possibilities, the battery charging problem should first be fully diagnosed, then the power wiring should be carefully inspected and if needed, the main power relay jumpered during a sealing operation to determine the

source of the problem. The auxiliary engine fails to start until repeated attempts succeed and this occurs mostly when it is hot. This most likely is related to the battery problem, but the ignition switch should be replaced and heat shielded as well. The air compressor over temperature safety switch may be causing a voltage drop when engaged. It needs to be inspected and a resistor may need to be added in-line to reduce the current flow.

- ***Spare sealant hose*** - It would be prudent to fabricate a spare heated hose for the Sealzall. The Cimline hose has already been procured and while the Sealzall is back at UC-Davis, it would be an expedient time to modify the hose.

Sealzall Upgrade Option

The Sealzall was an altogether new machine development effort, unlike any of the preceding longitudinal crack sealing projects. This unique prototype has gone from conceptual design through development, followed by extensive field testing and modification to reach successful trial deployment status in Caltrans District 11. Although the exact reproduction of the prototype is surely feasible, it would prove far more beneficial to resolve the limitations of the prototype discovered during deployment through various upgrades. This venture would probably be a year upgrade project to the existing Sealzall machine, followed by a year of field support. The advantages of upgrading the existing Sealzall prototype are time and cost savings.

- ***Upgrade PLC controller*** - As a time saving measure, the Sealzall was developed with a minimal PLC controller, which was a carryover from the previous crack sealing machine. As the complexity of the automatic control scheme evolved, the necessity for more PLC inputs and outputs (I/O's) increased. The current PLC has a limited amount of possible I/O's and that limit was reached early in the Sealzall development process. There was barely enough I/O's for basic operation and many desirable enhancement control functions and feedback information features had to be neglected. The existing limited PLC should be replaced with an available expandable PLC in the same family of controllers, which allows for the desired expansion of function, but uses the same basic programming code.
- ***Additional I/O integration*** - Removal of the I/O limitation by switching to an expandable PLC enables the incorporation of several additional features that would benefit the Sealzall's operation. Additional input data and control would improve safety, make the machine more robust, and simplify operation.

- ***Solve air compressor overheating issue*** - The air compressor overheating problem will certainly need to be resolved. It is critical that the air compressor be able to run continuously regardless of the ambient temperature. The solution may involve remounting the air compressor components, larger oil coolers, or possibly replace the current system.
- ***Chill the electrical control box*** - The Sealzall PLC overheating problem can be solved by cooling the electrical control cabinet. The installation of a fan to circulate ambient air has helped on mild days. On hot days, the ambient air temperature on the highway can easily exceeds the PLC operating temperature. In this case, simply circulating air is not helpful. Instead a means to actively chill the cabinet needs to be established. A commercially available air powered vortex cabinet cooler would be the simplest method to provide cooling, but this is dependent on the air compressor overheating problem being resolved. This is the reason a cabinet cooler has not already been tested in the field.
- ***Electric heated recirculation cradle*** - The Sealzall recirculation cradle connects the sealant wand to the sealant kettle to enable hot sealant to be circulated through the hose returning to kettle. The Sealzall standard operating procedure is to heat and fill the kettle with sealant and then recirculate hot sealant through the hose before leaving the maintenance yard. While driving out to the work site, the kettle burner is off, but hot sealant is continually circulated through the hose. Therefore, it is essential that the cradle provides a positive and safe connection to the kettle. The current design is trouble free, but it requires the operator to use a propane torch to heat the cradle to make the connection. It would be a significant improvement to redesign the cradle to incorporate an electric heater, but would require additional I/O and therefore an upgraded PLC as well.

Second Machine Build Option

If the priority within Caltrans is to identify a source to acquire or procure additional Sealzall machines, the second machine build project would be the best option. The goal of the recent Sealzall project was prototype development. A potential follow-up project could be focused on advancing the Sealzall machine design to facilitate manufacturability. This option would be a multi-year build project, but potentially the existing Sealzall prototype could remain deployed in District 11 during the process. In addition to the Sealzall upgrades discussed in the

previous section, the following is a list of additional upgrade options which could be considered if building a new machine is explored.

- **Redesign electrical wiring** - The Sealzall wiring diagram would not change much, but the electrical system should be redesigned to be more modular thus simplifying reproduction and maintainability. A drawing providing detailed information concerning conduit runs, mounting, and conduit fitting needs to be developed.
- **Increase sealant hose size** - The electrically heated sealant hose is based on the largest commercially available product with a $\frac{3}{4}$ inch inside diameter. The Cimline hose is very expensive to purchase and then it has to be modified for use on the Sealzall. The sealant flow through this hose is barely sufficient. It would be an enhancement to build a heated hose from scratch and increase sealant hose size to 1 inch, which will include increasing the wand size and modification of the recirculation cradle.
- **More powerful cartridge heaters** - The Sealzall sealant passage runs through the truck chassis and connects the kettle sealant pump to the sealant hose. The sealant passage has to be heated to facilitate hot sealant flow. Initially, the entire length of this passageway was heated by a series of 24VDC cartridge heaters inserted into the multiple pipe sections. The cartridge heaters alone proved to be less than sufficient to heat the passageway on chilly days. External heating pipe wrap was added to the passageway sections to provide extra heating capacity. The current passage heater scheme is sufficient, but on cold days it is slow to heat. It would be better to increase the size of cartridge heaters to enhance the passage heating capability. A surface heat wrap to the hose connection joint on the front bumper may also be added to mitigate a chronic cold spot.
- **Wand analog seal flow control** - With the additional I/O available with the upgraded PLC controller, it would be beneficial to upgrade the digital flow switch on the wand with an analog control switch. This would simplify flow control adjustment for the worker holding the wand in the manual sealing operational mode. The current method is complex and involves a pattern of pressing and holding a single button.

SEALZALL CRACK CLEANING

Highway pavement cracks collect debris and vegetation, which must be removed prior to sealing. Utilizing high production crack sealing equipment requires an equally large supply of clean cracks to seal. Sealzall initial testing was obstructed because of an inability to identify locations with long stretches of relatively clean highway cracks to seal. A significant research effort was devoted to developing an efficient crack cleaning method in order to enable the Sealzall to operate on highways with debris filled cracks. Ultimately, this effort stalled and the Sealzall was relegated to sealing sections of highway with new shoulders where the longitudinal cracks could be expected to be relatively clean. This restriction drastically limits the areas where the Sealzall can be utilized, but having these newer, clean cracks, has enabled the Sealzall machine testing and development to move forward.

In Caltrans' District 11, a long-term strategy is emerging which addresses the absence of efficient crack cleaning methods, or equipment by prevention. Starting by promptly sealing the transition joints after AC shoulders are replaced and committing to ensure these joints remain sealed thereafter, ensures that the build-up of vegetation and debris never has a chance to occur, thereby avoiding altogether the additional expense of aggressive cleaning operations. Regarding existing shoulder edge joints which are already filled with debris and vegetation, these were left unsealed until restoration and then were sealed. Sealing a joint without thorough cleaning is essentially a waste of resources since the seal will not last.

A more conventional and proactive approach would be to support a research effort to test commercially available systems or develop innovative new equipment designed specifically to quickly and efficiently clean longitudinal joint cracks. A description of possible high production joint crack cleaning equipment is presented in the following section, which presents the findings and recommendations based on research testing completed on the highway during the Sealzall initial testing phase.

SUPPLEMENTAL CRACK CLEANING REPORT

Crack debris and vegetation has always been a Caltrans maintenance concern. Weeds growing out of longitudinal cracks are as unsightly as they are detrimental to pavement longevity. This vegetation was typically sprayed with herbicide along the roadside. The resulting lack of vegetation roots combined with pavement displacement due to thermal cycles made the debris easier to dislodge with compressed air alone. Currently, with the mandated reduction in herbicide use, crack vegetation is allowed to essentially grow unimpeded. The prospect of instigating a renewed spraying of longitudinal crack vegetation with herbicide is improbable since it would always rank lower in priority than fulfilling the mandated roadside requirements, which are already chronically short on resources.



Figure 7. Typical Unsealed Longitudinal Joint and Same Joint Sealed with Proper Cleaning

Crack Cleaning for Crack Sealing

In general on the highway, in-lane cracks are fairly debris free and can be sealed effectively with little or no cleaning. In the worst cases, a simple blast of compressed air is typically all that is needed to clean the cracks prior to sealing. This is due in large part to traffic flow effects. The in-lane cracks appear to experience a vacuuming effect as high speed traffic passes over. The in-lane debris and moisture is sucked out and continuously blown out to the sides of the road where it inevitably collects in the longitudinal edge joints. So whereas the in-lane cracks are reasonably debris free and dry, the longitudinal edge joints are continually being

loaded with debris and moisture. Vegetation also does not survive well within the traffic lanes but thrives away from traffic along the edge where it has additional moisture and plenty of fresh dirt. Longitudinal crack vegetation even thrives in the State's most desolate desert areas. Since sealing longitudinal edge joints is the best targeted utilization of the Sealzall operations, the problem of highway longitudinal cracks being packed full of debris and vegetation is a major impediment to Sealzall deployment. The images in Figure 8 of failed seals were taken at the same highway pavement section and on the same day "as is" without any cleaning. They clearly illustrate the difference in vegetation and debris built-up between in-lane and longitudinal joints.

Eastbound Interstate 80 near the Northgate exit



Figure 8. Failed In-lane Seal between Lanes 1-2



Figure 9. Failed Longitudinal Edge Joint Seal

Sealing Without Crack Cleaning

Placing hot applied polymer modified sealant (Crafco) on an edge joint full of debris is ineffective and leads to AC shoulder deterioration. Longitudinal highway joint cracks are classified as "Working Cracks" meaning they open and close up to 50% with the daily and seasonal change in ambient temperature. When sealing a longitudinal joint filled with debris, the applied sealant preforms essentially like a band on the road surface and fails to bond to the crack walls. As the road cools and the crack consequently widens, the sealant band splits and the seal is permanently compromised. Application of the sealant in a cold weather cycle, when the crack is widest, is good common sealing practice. However with the next hot temperature, the band thins and splits during the following cold cycle. Either way the integrity of the expensive seal will generally only last a year or two. The sealant manufacturer, Crafco, has an informational YouTube video describing this effect which may be available at...

<http://www.youtube.com/watch?v=7Aa1GrK0RLY>

Another problem with not cleaning longitudinal cracks is that allowing incompressibles to remain in a working longitudinal PC/AC crack leads to AC shoulder lipping. As the pavement temperature lowers, the cracks fill with dirt and small rocks. Then as the pavement temperature rises daily and seasonally, the crack closes. Since the crack is now full of incompressible debris, large pressures develop in the crack interface. The crack compression force pushes some debris out of the crack toward the surface, but deeper in the crack the pavement must do the displacing. The AC pavement side of the crack is flexible, so it displaces in the only possible direction, upward. This causes a mound to form on the AC side of the crack. When the pavement subsequently cools and the crack widens again, debris refills the crack space and the process repeats. Each successive cycle pushes the AC edge mound or lip higher, and it becomes a fairly common traffic hazard (Figure 10). To mitigate the hazard, a pavement planer is used to grind down the lip and in the process chunks of stressed AC in the shoulder crack wall become dislodged creating a much wider crack.



Figure 10. Shoulder Crack Lipping – Hwy 160

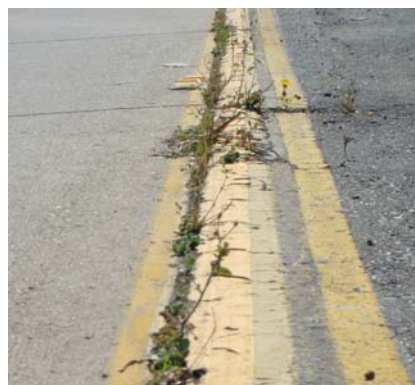


Figure 11. Joint Vegetation - Hwy 160

Removing vegetation from longitudinal cracks usually represents one of the biggest challenges in crack cleaning. The weeds that can thrive in highway cracks are well established and very durable. Their roots reach very deep in the crack and tightly grip the jagged edge of the AC shoulder (Figure 11). High pressure air blasts may dislodge the soil, but the vegetation will remain being held in by sturdy roots. Scraping the vegetation out of the crack is the only practical option, but the jagged AC edge helps protect the roots from being cut efficiently. By utilizing hand scrapers and wire wheels, much of the vegetation can be removed but at substantial cost. Still, the toughest weeds will remain and sealing over them will not always kill them. Vegetation shoots leave pores in the sealant where the weeds can continue to grow and

create a pathway for moisture to continue entering the crack. As a test, an excessive amount of time and labor was invested in an effort to eliminate all vegetation from a particular longitudinal joint crack on Hwy 160 prior to sealing. Ultimately, about 95% of the vegetation was completely removed and what remained was very distressed indeed. Still, a small amount of vegetation remained which then survived the hot sealant application and ultimately compromised the seal (Figure 12). The test clearly reveals that sealing over any small amount of vegetation will significantly compromise the longevity of a joint seal.



Figure 12. Vegetation in Seal after only 6 Months - Hwy 160

Sealing With Proper Crack Cleaning

Crafco claims long-term monitored FHWA studies predict cracks routed and sealed achieve more than twice the service life vs. non-routed and sealed cracks. While many environmental factors can affect these results, it is unquestionable that seal longevity is tantamount to cost reduction. Highway crack sealing operations are very expensive and represent a major maintenance budget investment. Therefore, extending the functional life of the seal with proper cleaning procedures is of vital interest to Caltrans maintenance. Not only does extending the functional life of the seal spread the application cost over many more years effectively reducing the cost, but it also extends the interval between major pavement rehabilitation.

Ideally, all debris and vegetation should be removed from longitudinal edge joints prior to sealing, which is not very realistic or cost effective. At a minimum all the vegetation and debris should be removed down at least 1-3 inches into the crack depending on the crack width. This provides a reservoir for the sealant to reside and bond to crack walls. The sealant reservoir is protected from traffic and enables the seal to survive pavement thermal displacements, thus providing for maximum seal longevity. Incompressibles still remain in the crack, but at a greater

depth where their effects on lipping are reduced. The depth of crack cleaning is related to the crack width to create a reservoir for sealant application with a shape factor (depth/width) greater than two.

Longitudinal Joint Seal with Proper Crack Cleaning



Figure 13. Effective Joint Seal - Hwy 160



Figure 14. Effective Joint Seal - Interstate 8

Crack Cleaning with the Sealzall

The Sealzall was developed with an on-board high pressure, high volume compressor system (90 cfm @150 psi) that provides nominal crack cleaning capabilities to remove light debris prior to sealing. Traditionally, heavy cleaning operations were conducted well prior to the longitudinal sealing operation and utilized separate equipment. Herbicide spraying and multiple blowing operations with towed air compressors were common preparations in the past. In the current climate of reduced workforce, a method of cleaning the crack as part of the sealing process must be developed. Operations that rely on advanced preparations and extra tasks are simply no longer practical. Ideally, if the heavy cleaning operation is to run in connection with high speed sealing, it should be capable of efficiently clearing the joint crack in one pass. Since in practice compressed air alone proved to be utterly ineffective (Figure 13). Note: the debris was wet and soft on the day of this demonstration, which is the best possible scenario. Once the debris is dry and hard, an air blast produces hardly any visible crack cleaning gain at all. Since the performance of the Sealzall is associated with producing high quality seals, it is essential that the resulting seal be of the highest quality for the machine to succeed. Since the initial Sealzall test site on Highway 160 with its heavy debris and vegetation, a crack cleaning tool needed to be developed quickly to enable Sealzall operational testing to move forward. Even though heavy

crack cleaning capability was not part of the original scope of the Sealzall project, it was a major component of the initial Sealzall testing program.

Crude crack cleaning attachments were developed for the Sealzall to experiment with cleaning debris and vegetation from longitudinal edge joints. The attachment mounted to the longitudinal carriage the same way the sealant wand attaches for longitudinal sealing operations (Figure 14). The cleaning wheel attachment mounting has five inches of lateral travel, that once put in the crack, enables the wheel to self-track the joint. The driver then only needed to steer the truck to keep the wheel near the center of travel. The wheel was initially driven by a 12VDC motor and then switched to a hydraulic motor to increase wheel torque. The wheel control was added to the in-cab controller, so the cleaning operation could be operated from the highway shoulder without a lane closure.



Figure 15. Crack Cleaning Test - Interstate 380

Two cleaning wheels were fabricated. A thin steel cutting blade with carbide teeth could cut through hard dirt and gravel and a wire wheel was utilized to remove vegetation and loose debris. Highway testing of the cleaning attachment was successful and did produce a relatively clean crack, but the time investment was extreme. Typically, three passes were required to properly clean a crack full of packed debris and vegetation. Even worse, the speed of each cleaning pass was nearly half the speed of longitudinal sealing. Even though sealing wide longitudinal joints can sometimes require two passes, one to fill and the second to recap, the wheel attachment cleaning operation is still about four times more time intensive than the sealing process. When working with Caltrans maintenance crews in District 4 and 11, it became clear that the added time and worker exposure required to clean the crack with these attachments would not be reasonable on a large scale. An efficient method of removing heavy debris and vegetation from longitudinal joint cracks in a single pass would need to be developed to

effectively enable Caltrans to utilize the Sealzall on anything other than already clean longitudinal joints.

Cutting Blade Attachment Cleaning



Brush Wheel Attachment Cleaning



Figure 16. Sealzall Crack Cleaning Attachments – Hwy 160

Crack Cleaning Router

Routing cracks prior to sealing is commonly recognized as the best crack cleaning technique to achieve the greatest possible seal longevity. Crack routing produces a consistent and controllable sealing reservoir of any desired dimension for optimum seal adhesion and longevity. Routing removes all debris and vegetation from the sealing reservoir in a single pass. Air blast and wheel crack operations are passive cleaning methods that only clean the existing crack, but routing provides the added benefit of cutting the AC shoulder to create the desired sealing reservoir. At times the crack may be tight or even closed, preventing sealant from entering the crack and producing a seal band with poor longevity. Crack routing can open up a tight crack by cutting the AC shoulder to create the desired seal reservoir. Initial testing with an impact router proved that this type of router can cut/clean the crack reservoir at speeds similar to Sealzall longitudinal sealing.

In-lane crack routing is very tedious work, wrestling the heavy router manually trying to follow a jagged random crack. Routing a longitudinal joint crack is a far easier task since it is relatively straight. The difficulty of steering the router is less and a guide wheel can be added to make the cutting head self-track the longitudinal joint. This enables the router to travel at maximum cutting speed, which in the case of removing mostly debris and vegetation could reach speeds up to five miles per hour.

Pavement Routers

To efficiently clean enough longitudinal joint cracks to adequately support Sealzall high production crack sealing capabilities, some type of high speed, single pass crack routing operation needs to be developed. Self-contained impact pavement routers that are manually controlled are readily available (Figure 17). They use consumable carbide tipped star wheel cutters (Figure 18). Pavement planer and wheel saw attachments are also available, which mount on Skid-Steer tractors (Figures 19 & 20). The impact cutting head and wheel saws are appropriate for crack cleaning, while the planer is typically used to cut a flat surface. Since there is often some degree of pavement lipping associated with longitudinal cracks needing to be sealed, including a pavement planer option with a crack cleaner would be a major multi-functional tool bonus.



Figure 17. Joint Routing - Interstate 380



Figure 18. Impact Router Cutter

Neither the impact router, nor the wheel saw are perfectly suited for longitudinal crack cleaning without modifications. Standard impact router cutter star wheels have a shallow depth of cut, and the wheel cutter width cuts too wide for most cracks. Both of these shortcomings can be overcome, but custom modifications to the cutter wheels would necessitate significant redesign. Also, the means to mount the cutters to self-track the longitudinal crack would have to be developed for either device. Ideally, the cutting system could be truck mounted to enable crack routing to be conducted from the shoulder without lane closures to achieve the greatest cost efficiency.

Cleaning crack ejects a significant amount of dust and debris in the process. The dust cloud and flying debris creates a traffic hazard when operating adjacent to live lanes and negatively impacts air quality. Incorporating a vacuum system to manage the dust would be a

valuable feature to include. Potentially, the vacuum system could be strong enough to also clean the crack following the routing. This would eliminate the need for a trailing blast of compressed air to clean the crack which creates its own dust. An ideal candidate for a commercially available vacuum capable of handling the large amount of debris routed from a continuous longitudinal joint crack would be a three-stage cyclonic filtration system (Figure 21).

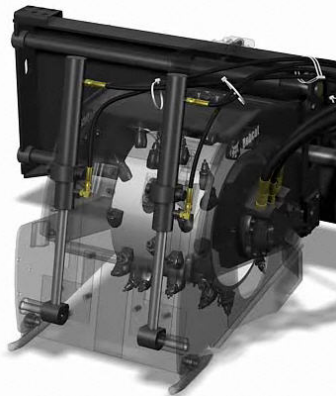


Figure 19. Bobcat Pavement Planer



Figure 20. Bobcat Wheel Saw

CRACK CLEANING MACHINE RECOMMENDATION:

The Sealzall high production joint sealing capability requires an equally large inventory of clean joint crack to seal. Should Caltrans be interested in pursuing comprehensive Sealzall machine deployment statewide, it is recommended that the development of an efficient and high speed longitudinal crack cleaning machine should also be considered. Special equipment will have to be developed for this task, but it should deliver the utmost cost and safety benefit to Caltrans maintenance and ultimately prove to be an indispensable part of the sealing operation. Of the techniques tested, crack routing/sawing has been identified as the most efficient technique. The high production crack cleaning machine should be designed to clean longitudinal joints in a single pass at speeds up to five miles/hour and collect all cutting dust and debris. Like the Sealzall, the crack cleaning machine should be capable of operating along either shoulder and in a moving closure. Therefore, the machine should be designed with full in-cab controls requiring a medium level of automation to get workers off the highway.



Figure 21. Vortex Vacuum System



Figure 22. One Pass Routed Joint

SEALZALL LIFE CYCLE COST ANALYSIS

Constructing a straightforward cost comparison between the traditional manual sealing process and the Sealzall sealing operation is inherently problematic. On a functional level, the Sealzall makes it possible for maintenance crews to access hazardous highway locations or traffic sensitive areas, which are for all practical purposes unreachable by workers exposed on foot. On a more fundamental level, the considerable boost in Sealzall production rate translates into more lane miles of highway pavement sealed as opposed to a simple comparison of sealing the same lane miles in less time. Since the sole purpose of crack sealing is to extend pavement life, and there is a sizeable deferred rehabilitation cost saving benefit in having pavement cracks sealed on the highway, it stands to reason that there is certainly an added benefit for sealing more lane miles. Therefore, the Sealzall produces a double benefit. First, there is the direct cost benefit of being far more efficient than manual methods at sealing highway joint cracks at current yearly sealing distance levels. In addition, there is a soft cost benefit due to the dramatic Sealzall sealing production rate increase, which enables a conventional effort to seal far more highway cracks delivering a considerable deferred rehabilitation cost benefit [2].

Various studies have endeavored to quantify these pavement preservation soft cost savings directly, with various levels of success. In 2006 an alternate cost comparison was completed as part of a University of California, Davis business case development report (pages 14-16) [10]. The industry recognizes the inherent value, but the prevailing focus is on reducing direct costs which are generally a more pressing concern. However, the neglect of pavement maintenance shortens the interval between costly pavement rehabilitation, which merely increases maintenance direct costs over the long term. Typically, the industry seeks to

understand the balance between investing in pavement maintenance near term to earn significant long term pavement preservation soft cost saving benefits. Regardless of how the direct and soft pavement maintenance cost statistics are determined, their complex association prevents them from merely being combined together to establish an accurate composite Sealzall cost benefit analysis. Instead of attempting to evaluate and integrate the soft cost benefit, in this analysis the pavement preservation term will be accounted for and effectively factored out from a maintainability perspective. But first the case will be presented that justifies the narrow focus on the sealing of longitudinal joints on the highway.

Longitudinal Joint Sealing Focus

Longitudinal joints are inherently working cracks while in-lane cracks are typically less so. 80% of the water infiltrates into the road sub-base through these joints [1], which is a principal contributing factor in triggering major pavement failures. Also if these joints go unsealed, incompressibles fill the void which triggers PCC spalling and AC shoulder lipping. Therefore in regards to crack sealing, the sealing of longitudinal joint cracks provides the greatest benefits and should therefore be ranked as a high priority task. In addition, AC/PCC joints are generally sealed with hot applied rubberized asphalt sealant in a continuous process while in-lane PCC cracks and joints are segmented requiring fixed lane closures and are increasingly being sealed more effectively with urethane polymers.

Maintainability Cost Model

In 2011 Caltrans had the responsibility to maintain 16,410 lane miles of rigid pavement highway, which represents 33% of Caltrans total pavement inventory [3]. This corresponds to 2,701 center lane miles that calculates out to 10,804 miles of longitudinal edge joints, which is approximately four times the center miles for divided highways. Preferably all of these edge joints should be sealed, which would maximize pavement life and minimize Caltrans pavement maintenance costs. According to FHWA study results [4], a properly installed hot applied rubberized asphalt joint seal should be expected to remain effective for an average of five years, with the predominant failure mode being adhesion or cohesion loss. Consequently, Caltrans should strive to seal approximately 2,161 miles of longitudinal edge joints a year to achieve full maintainability of these pavements. Viewing the Sealzall cost benefit analysis from this

maintainability perspective effectively factors out the soft pavement preservation cost benefit term and produces an essentially normalized and accurate direct cost comparison.

Based on field observations, a standard maintenance crew applying hot applied rubberized asphalt sealant can expect to seal about one mile of longitudinal pavement joint a day with conventional manual methods. Whereas the Sealzall trial deployment with Caltrans District 11 crews as discussed previously and reported in the Caltrans IMMS data [5] showed that under normal operating conditions, about six miles per day sealing similar longitudinal cracks is expected. Therefore, considering an arbitrary 180-day work year, Caltrans would consequently need twelve dedicated crews to meet this goal.

In comparison, Caltrans Maintenance utilizing the Sealzall machine could achieve this maintainability goal with just two machines and two crews.

Table 1- Sealzall Maintainability Cost Savings Model

<i>Maintainability Model</i>			
<i>Caltrans Costs to Longitudinal Seal 2,161 Lane Miles per Year</i>			
	Sealzall	Manual	
Basic Sealant Cost (per mile)	\$672	\$672	[USD]
Total Sealant Cost	\$1,452,192	\$1,452,192	[USD]
Caltrans Sealing Crews (5 person crew)	2	12	[Crews]
Basic Operational Cost Rate (per crew, see Table 2)	\$1,696	\$1,619	[USD/day]
Basic Operational Cost (per day)	\$3,392	\$19,428	[USD]
Average Distance Sealed (per day)	6	1	[Miles]
Total Operational Cost (180 work days/year)	\$610,560	\$3,497,040	[USD]
Worker Exposure Safety Costs (per year, see Table 4) (on foot)	\$0	\$42,100	[USD]
Worker Injury Cost (on foot) See reference [10]	\$0	\$9,366	[USD]
Public Traffic Impact Costs (per year, see Table 6)	\$207,115	\$1,242,575	[USD]
Calculated Total Sealing Cost (per year)	\$2,269,867	\$6,243,273	[USD]
Calculated Cost Difference (per year)		+\$3,973,406	[USD]
Caltrans Cost Savings (per year)	\$4.0 Million		[USD]

Example formula: *Calculated Total Sealing Cost = Total Sealant Cost + Total Operating Cost + Worker Exposure Cost + Worker Injury Cost + Public Traffic Impact Cost*

The worker exposure safety cost is placed at zero because with the Sealzall operation the workers are not directly exposed to traffic. Similarly, the public traffic impact cost is significantly reduced because the Sealzall moving closure allows traffic to run at full speed and rolling closures of ramps are momentary. It should be noted that there are many similarities between the manual and Sealzall sealing operations as well. These include crew size, number and type of support vehicles, amount of sealant applied per mile, seal quality and appearance and the length of the workday. Crack cleaning is not included in these calculations and would be an added cost for either method.

Sealing Basic Operational Cost Analysis

There are basic operational costs essential to conducting longitudinal joint sealing on the highway regardless of the application technique utilized. These basic costs include trained workers, equipment and supplies. Generally, the standard Caltrans sealing labor crew consists of five workers with 2-3 workers on the pavement and 2-3 workers providing traffic control, support and supervision. To provide a fixed temporary lane closure for the manual sealing operation, Caltrans maintenance crews typically deploy four vehicles: a cone body truck to place closure, dump truck with a TMA to shadow the utility body truck with trailered kettle and a dump body truck to carry pallet(s) of sealant blocks. For the Sealzall longitudinal sealing operation which always is conducted either in a moving lane closure or from the shoulder, Caltrans maintenance crews generally deploy: a utility body truck with signboard, a dump truck with arrow board, and a TMA dump truck to shadow the Sealzall truck. The actual vehicles utilized vary from operation to operation based on availability and have a negligible effect on the overall cost. Table 2 lists Caltrans standard billed rates for equipment rental and labor derived from IMMS records. To determine the estimated rental rate for the Sealzall, the Caltrans internal equipment billing cost values cover equipment acquisition, salvage value, and maintenance. To establish the expected Sealzall rental rate, the projected equipment costs were applied to the following standard Caltrans Division of Equipment rental rate formula.

Example formula; Caltrans Equipment Rental Rate = (Capital value – Salvage value) / Useful life in years + Direct (OE for engineering/mechanics) + Indirect costs (Administration support & distribution)/365

Using an estimated Sealzall acquisition price of \$300,000, 8 year service life, \$15,000 salvage value and \$6,750 for a combined Direct and Indirect costs (analogous to snow plow duty); these values calculate out to \$116 per day. Due to the inherent complexity of the Sealzall, it is logical to expect that the cost to maintain the machine in service would be greater than the cost of maintaining a standard crack sealing truck and sealant kettle rig. But when considering the Sealzall's increased production rate, a more accurate comparison would actually be to the maintenance cost of six sealant kettle trailer and truck rigs. It is currently unknown which of these costs would be greater without further Sealzall maintenance history, but in the meantime it seems reasonable to consider the Caltrans incurred maintenance costs to be nearly equivalent.

Table 2- Direct Fixed Cost per Day

<i>Maintainability Model</i>				
<i>Longitudinal Crack Sealing Direct Fixed Cost per Day</i>				
		Sealzall	Manual	
Labor	(5 Worker Crew @ \$300 Day)	\$1,500	\$1,500	[USD]
Sealant Kettle	(1 per day)	\$0	\$12	[USD]
Dump Body Truck	(2 per day)	\$68	\$68	[USD]
Utility Body Truck	(1 per day)	\$12	\$12	[USD]
Cone Body Truck	(1 per day)	\$0	\$27	[USD]
Sealzall Truck	(1 per day)	\$116	\$0	[USD]
<i>Sealing Direct Fixed Cost</i>	<i>(per day)</i>	<i>\$1,696</i>	<i>\$1,619</i>	<i>[USD]</i>

Worker Safety Cost Analysis

There are also indirect benefits realized through safety enhancements. Employees are exposed to a certain level of risk whenever they are working on or near the roadway. Injury data during crack sealing operations was previously evaluated in reference [10], adjusted from 2,221 miles to 2,161 miles and included in Table 1. This section estimates exposure costs due to fatality rates.

Since 1972, Caltrans has experienced 49 deaths due to accidents caused by errant drivers [6]. This averages to roughly 1.2 fatalities per year. The cost of a worker fatality has been previously reported as \$6 Million [7]. Accordingly, a risk cost per person-hour on the roadway can be developed for a 52-week year with 8-hour workdays. A fatality accident rate is calculated by assuming that Caltrans has roughly 21,000 employees with 25% of the employees working on

the road and spending 50% of their time in the field. Table 3 summarizes the results of this calculation.

Table 3- Calculated Exposure Cost Rate

<i>Maintainability Model</i>			
<i>Calculated Exposure Cost Rate - Fatalities Only</i>			
Assumed Number of Caltrans Employees	21,000		
Assumed Number of Caltrans Employees Exposed	5,250		
Assumed Caltrans Employees Time Spent on Road	50%		
Calculated Man Hours On Road Rate (per year)	5,460,000	[Hours]	
Calculated Average Fatal Accidents Rate (per hour)	2.18×10^{-7}		
<i>Traffic Exposure Fatality Cost Rate</i> (per hour)	<i>\$1.30</i>		<i>[USD]</i>

Traditional manual highway longitudinal crack sealing operations are conducted in temporary lane closures on foot and frequently adjacent to high speed traffic. There is an inherent safety cost to Caltrans associated to workers exposed to this direct traffic hazard quantified in Table 4. One of the unique benefits of conducting highway longitudinal crack sealing operations with the Sealzall machine is that all worker direct exposure to traffic is eliminated. The following table calculates the Sealzall safety benefit in terms of the maintainability model described previously.

Table 4- Worker (On Foot) Exposure (Fatalities Only) Safety Cost

<i>Maintainability Model</i>			
<i>Exposure Safety Cost to Manually Seal 2,161 Miles of joint crack</i>			
Number of Crews Needed (per year)	12		
Assumed work year	180	[Days]	
Average Time Spent on Road (per day)	5	[Hours]	
Exposed Crew Size	3	[Workers]	
Calculated Exposure Hours (per year)	32,400	[Hours]	
Calculated Exposure Cost Rate (per hour, see Table 3)	\$1.30	[USD]	
<i>Total Exposure Fatalities Cost</i> (per year)	<i>\$42,100</i>		<i>[USD]</i>

Employee safety is far more important than can be expressed in a simple dollar value as done in Table 4. To get a different perspective, a risk statistic is generated by considering a hypothetical employee. This employee is assumed to have a 22-year career and spends 50% of their time on the road. This employee will thus accumulate 22,880 road-hours over their career. Based on these road-hours and the calculated average accident rate per hour from Table 3, the employee has a 0.5% chance of a fatal accident (nearly a 1 in 200 chance). Allowing employees to complete their jobs from the relative safety of a vehicle should reduce risk significantly. The Sealzall accomplishes this task by allowing the two employees, who would be on foot in a traditional crack sealing operation, work within the confines of the Sealzall's cab. Eliminating the necessity to establish fixed lane closures for the Sealzall operation even further reduces worker direct exposure to high speed traffic which is a standard requirement for all traditional manual crack sealing operations.

Public Traffic Impact Cost Analysis

There are public externalities associated with establishing temporary fixed lane closures on the highway to safely conduct roadwork that causes traffic to slow. The time cost of traffic in the Sacramento region (excluding commercial trucks) has been estimated to be \$16.79 per person-hour [9]. Due to the high volume of traffic on highways maintained by Caltrans, even a small reduction in traffic speed can lead to serious costs. Using 2011 Annual Average Daily Traffic data (AADT) [8] the simple average traffic volume for all reported highways in the state was calculated as 64,075 vehicles. Assuming constant traffic over the course of the day, this averages to 2,669 cars per hour. Since traffic is likely heavier during the day, this will serve as a conservative estimate. Table 5 shows the estimated public costs for a 2-mile long traffic slowdown with one person per vehicle using these numbers.

Table 5- Calculated Public Traffic Impact Cost Rate

<i>Maintainability Model</i>			
<i>Calculated Public Traffic Impact Cost Rate for 2-Mile Slowdown</i>			
Assumed Cost of Congestion	(per person-hour)	\$16.79	[USD]
Assumed Nominal Traffic Speed		65	[MPH]
Assumed Speed Reduction		5	[MPH]
Calculated Average Time Added Per Vehicle		9.23	[Seconds]
Calculated Cost Per Vehicle		\$0.043	[USD]
Assumed Daily Traffic Volume	(per hour)	64,075	[Cars]
Calculated Hourly Traffic Volume	(per hour)	2,670	[Cars]
<i>Calculated Traffic Impact Cost</i>	<i>(per hour)</i>	<i>\$115</i>	<i>[USD]</i>

Example calculation: Average time added for a 5MPH slowdown = Delay time x 2 miles

60 MPH = 60 Seconds/Mile 65MPH= 55.385 Seconds/Mile

5MPH Slowdown = 4.615 Seconds/Mile x 2 Miles = 9.23 Seconds

This high public externality is reduced by completing the crack-sealing task quicker or by reducing impact on traffic speed. The Sealzall operates in a moving lane closure and thus has a lesser impact on traffic and the associated costs. The Sealzall longitudinal joint sealing operations seal across entry and exit ramps with quickly rolling ramp closures, where fixed ramp closures must be approved by Caltrans Traffic Operations and posted days in advance on the highway. Furthermore, should highway traffic congestion occur in the vicinity of the sealing operation for any reason related or not, the entire Sealzall operation can be at any instant driven completely off the highway.

Table 6- Public Traffic Impact Cost

<i>Maintainability Model</i>				
<i>Public Cost to Manually Seal 2,161 Miles of Joint Crack</i>				
		Sealzall	Manual	
Length of Highway Lane Closure	(per day)	5	5	[Hours]
Distance Sealed	(per day)	6	1	[Miles]
Total Fixed Lane Closure Time	(per year)	N/A	10,805	[Hours]
Total Moving Lane Closure Time	(per year)	1,801	N/A	[Hours]
Calculated Cost	(per hour, see Table 5)	\$115	\$115	[USD]
Total Public Cost	(per year)	\$207,115	\$1,242,575	[USD]

Example calculation;

Total Lane Closure Time = Length of Closure / Distance Sealed x 2,161

Total FIXED Highway Lane Closure Time = 5 hours / 1 mile x 2,161 miles = 5 x 2,161 = 10,805

Total MOVING Highway Lane Closure = 5 hours / 6 miles x 2,161 miles = 5/6 x 2,161 = 1,801

Example calculation; Total Public Cost = (total lane closure time) x (cost per hour)

Total lane closure time for FIXED closure = 10,805 x \$115 = \$1,242,575

Total lane closure time for MOVING closure = 1,801 x \$115 = \$207,115

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