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Area: Civil Infrastructure

White paper Title: Laser and Radar fusion for national critical need – advanced sensing technology for the infrastructure

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Dear TIP Officers:

Attached is the white paper which addresses our nation's critical need -advanced sensing technology for the infrastructure. As pointed out by our Government, national civil infrastructure is in poor condition, total funds needed to bring America's infrastructure back to good condition are estimated to be \$1.6T over 5-year period. This is the reason why infrastructure is the first priority of President Obama's stimulus plan. To get the poor civil infrastructure back to good condition, the first step is to measure/evaluate the civil infrastructure performance of highway, runway, road, bridge, etc. to know which road needs repair and which road is still in good condition. The Government has spent millions of dollars to support the research using fiber or stress sensor to monitor the bridge and railroad but the data collected are for local stresses test only, they cannot give a picture of the whole bridge or railroad stress or shape change, they cannot measure the slit, void and other defects underneath the pavement. The nation does not have the money and labor to use fiber or stress sensor to monitor 600,000 bridges and million miles of railroads/subways. Of course it is impossible to use fiber or stress sensor to monitor the stress of 4,000,000 miles of public roadways and the runways of 15,000 airports, it even cannot get the stress of one foot of the highway pavement. We must find a new sensing method.

In order to overcome the above problems, several macroscopic methods have been developed: dynamic core penetrator (DCP), falling weight deflectometer (FWD), Benkelman Beam (BB), and heavy rolling weight deflectometer (HRWD). The DCP must stop traffic to core the pavement so it cannot be used for the highway, runway and bridge. FWD is a good device, it uses a heavy hammer striking the pavement and deploys 8 sensors on the ground to measure the seismic wave to get the deflection, the traffic must be stopped and to measure one point needs 20 minutes; the next point may be 100 meters away. Obviously the speed of FWD is too low and it is a discrete not continuous measurement method. BB is a mechanic deflection measurement method, the speed is too low; to use it on bridge or highway the traffic also must be stopped. Only the HRWD can continuously measure the pavement deflection with highway speed of 55 MPH, but it cannot measure the important deflection basin and the pavement thickness and modulus thus the stiffness and hardness of the pavement, it also cannot visualize the slit, void, water and other defects underneath the pavement. It has 10 problems to be overcome.

Therefore under 3 phase-II contracts from the Army, SOCOM and AF for the civil infrastructure performance measurement, we have developed a laser and Radar fusion technology to overcome above problems to not only measure the deflection basin and thickness of the pavement to get the pavement stiffness and hardness but also penetrate the pavement to see the defects - slit, void, water, etc. underneath to get the 3-D road condition profile by incorporating with speedometer and GPS. Our 24' trailer is much shorter than the 53' HRWD and can be towed by a common truck to survey not only highways but also local roads; the continuous and nondestructive measurement speed can be up to 70 miles per hour, traffic is not necessary to be stopped or interrupted. By using our advanced sensing technology for infrastructure, the nation can save millions even billions of dollars and months even years of time. However, our current technology still has shortcomings; a more advanced technology is proposed - using laser slide on the trailer to measure the dynamic and static deflection basins for highway, runway and bridge which can get hundreds points per basin so we can use a set of new equations to get the pavement modulus, stiffness and other properties precisely. We do need TIP's support to do this high risk and high reward research to get transformational results. Please give your advices to our attached white paper proposal.

Sincerely,

Dr. Ronald L. Fletcher, VP and Dr. Alan Zhang, CTO

Fast, Nondestructive and Continuous Pavement Network Performance Evaluation System

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1. Statement of the Problems

1. 1. Nation's Critical Need for Infrastructure

The United States of America has 4,000,000 miles of public roadways, 600,000 bridges, and 15,000 airports. Crumbling pavements, aging bridges, and deteriorating transit is listed as the number one headache of America's top five transportation headaches while congestion is listed as the second. According to the data available at Federal Highway Administration, more than 50 percent of urban roads were in poor or mediocre condition (see Table 1).

Table 1. Pavement Conditions of Urban and Rural Arterial Highways (AASHTO 2009)

	Rural	Urban	All Major Roads
Poor	4%	26%	13%
Mediocre	15%	27%	20%
Fair	20%	11%	16%
Good	61%	36%	51%

The U.S. taxpayers spend money on poor roads twice: (1) to restore pavements in good condition and (2) to afford the additional vehicle operating cost. According to the American Society of Civil Engineering 2009 infrastructure report card, "Americans spend 4.2 billion hours a year in congested traffic at a cost to the economy of \$78.2 billion. Poor conditions cost motorists \$67 billion a year in repairs and operating costs." Maintaining a road in good condition is easier and less expensive than repairing a road in poor condition. Current state-of-the-art technology can be only partially utilized to measure pavement performance and identify repair needs during the initial deterioration to maintain the pavements in good condition. Therefore, the Critical National Need is the development of a device that utilizes *Advanced Sensing Technologies and Procedures* for measuring pavement performance of an entire road network with minimum or no disturbance to the traffic and public. The data collected from the device will be helpful for developing a carefully planned and proactive pavement management program to improve the accuracy of prioritizing and targeting fund for the road segments that need repairing, rehabilitation, or replacement. Unfortunately, until today there is no quantitative nondestructive testing method that is capable of continuously measuring pavement stiffness, hardness and other performances and detecting and visualizing defects underneath the whole pavement network at traffic speed. The Government has spent billions of dollars to support the research using fiber or stress sensor to monitor the bridge, railroad and subway but the data collected are for local (micro) stresses only, they cannot give a whole picture (macro) of the integrity of the bridge, railroad or subway, they also cannot visualize the slit, void and other defects underneath the pavement and measure the stiffness and hardness of the pavement. In addition, the nation does not have the money and labor to use fiber or stress sensor to monitor 600,000 bridges and near million miles of railroads and subways. Of course it is impossible to use fiber or stress sensor to monitor the stress of 4,000,000 miles of public roads and the runways of 15,000 airports. The routine procedure for pavement inspection is to use eye or listen the sound from hammer or chain, but the inspection is labor intensive and the speed is very low. Transportation Department also use visible camera including stereo to check the surface cracks, it is useful but it cannot determine if the underneath integrity of the pavement is bad or still good because the surface cracks may be caused by surface ice, thermal expansion, vehicle impact, etc. not the underneath defects. The pavement integrity underneath the surface is more important than the cracks on the surface. Besides, the visible camera cannot detect void and other defects underneath, and cannot measure the most important pavement properties – stiffness and strength to determine if the pavement needs major repair and should reach which layer, and what is the remaining life time.

In order to evaluate the pavement integrity especially underneath the surface, several methods have been developed: dynamic core penetrator (DCP), falling weight deflectometer (FWD), Benkelman Beam (BB), and heavy rolling weight deflectometer (HRWD). The DCP must stop the traffic to core the pavement so it cannot be used for the highway, runway and bridge. FWD is a good device, it uses a heavy hammer striking on the pavement and deploys several sensors on the ground to measure the seismic wave, but the traffic must be stopped and to measure one point needs 20 minutes. Therefore FWD is a slow and discrete not fast and continuous measurement method. The BB can measure the deflection and not true basin under load but it is a mechanical measurement method, the speed is too low; to use it on bridge or highway the traffic also needs to be stopped. Only the HRWD can continuously measure the pavement deflection with highway speed of 55 mph, but it cannot directly measure the pavement thickness and the deflection basin to get the modulus thus get the stiffness and strength of the pavement; it also cannot visualize the slit, void, water and other defects underneath the pavement. HRWD has 5 major problems:

1.2. Major Problems of HRWD

Quest Integrated, Inc. developed the first HRWD, Applied Research Associates, Inc. improved the system but the 2-step measurement principle is the same. The device uses exactly the same principles of the BB to measure the deflection except the HRWD cannot measure the deflection basin. It has following 5 major problems:

(1) It is very difficult to make the two-step measurement on the same point

To obtain accurate deflection measurements, it is essential for Quest/ARA that identical locations must be measured by subsequent optical distance sensors when the HRWD rolls forward 2.74 m (9 ft). If the HRWD turns slightly and the sensor measures a point other than the original location, an error about equal to the difference in elevation and unevenness of the expected point and the point actually measured will be introduced into the deflection measurement. This error could easily be several orders of magnitude higher or lower than the actual deflection. The only way to reasonably measure the deflection is to average the data in certain distance and set up a threshold to abandon unreasonable data if we want to use the two-step measurement method.

(2) It cannot measure the deflection basin

Instrumentation provided in HRWD measures only a single point deflection at a time when the wheel moves forward. It is impossible to measure the deflection basin created by the loading wheel. Measurement of deflection basin is very important to calculate the pavement modulus, modulus of subgrade reaction, joint load transfer efficiency, pavement stiffness and other pavement properties. The measurement of single point deflection cannot provide adequate data for measuring pavement properties and evaluating its performance. Basin measurement is a must.

(3) It cannot borrow the algorithm from FWD

HRWD measures the deflection and uses pavement thickness data from initial construction documents then uses the FWD software to backcalculate the pavement stiffness that is not proper because stiffness calculation requires pavement modulus that can only be obtained from the deflection basin but the HRWD cannot measure the basin (although the FWD can indirectly measure the discrete basin). In addition, the pavement thickness will change with time and road condition, it should be measured in-situ with the deflection basin together but HRWD cannot do.

(4) The trailer is too long

The 53' trailer needs a semi tractor with specially licensed driver to tow and it is too long for local road and state road measurement. If a 24' trailer towed by a F250 can be developed that will give great convenience for pavement survey on all roads.

(5) Using milk for calibration is not a good way

ARA uses milk for laser mounting position measurement or calibration, but the laser will penetrate the milk so the reading will change with time to create error. We need to find a special liquid that can not let the laser penetrate it.

The purpose of this research is to design a Fast, Nondestructive and Continuous Pavement Network Performance Evaluation System (**FNCNPES**) with measurement speed up to 70 MPH to solve all these problems. The system should be able to be used for fast highway, bridge, runway and roadway surveys and the end users will be the Air Force, Army, Navy, SOCOM, Coast Guard, transportation department, civil engineering agencies and others in the whole world.

2. Objectives of the Study

In order to satisfy above Nation's critical need and solve above unsolved problems the objectives of this research are: (1) Design the world's first **FNCNPES** with 3 subsystems – (a) short rolling weight deflectometer (SRWD) for dynamic deflection and basin measurement with traffic speed up to 70 mph. (b) Rotary laser slide deflectometer (RLSD) on the trailer for dynamic deflection and basin measurement with traffic speed to get hundreds points per basin, and (c) ground penetration Radar (GPR) for in-situ pavement thickness measurement. (2) Derive a set of equations and fuse the deflection basin data from SRWD or RLSD and the pavement thickness data from GPR to calculate the pavement modulus, stiffness, strength and other properties. (3) Combine the above data with GPS, distance encoder, CCD and inclinometer to get the world's first 3-D road condition profiles on the surface and underneath the surface to see if the road needs major repair, the repair should reach which layer, and what is the remaining life time.

3. Background and Significance of the Work

During the Phase-I and Phase-II researches for the Army, SOCOM and Air Force we have performed extensive literature search and listed the findings in the references. Since our approach is fast, nondestructive and continuous pavement measurement, it is not necessary to discuss the details of visual inspection, fiber/stress sensor, CCD camera, DCP, FWD, BB and laser ultrasonic, we only need to deal with the HRWD and we have discussed the major problems of HRWD to be solved. Table 2 listed the performances of existing HRWDs and the comparison with our **FNCNPES** (see the design later). From the table and literature search we can conclude that our **FNCNPES** is not a duplication of other ongoing or completed work even not a modification of the state of the current practice because as mentioned in our system design, we will give world's first design and produce world's first multiple sensor fusion system for fast, nondestructive and continuous pavement network performance evaluation with 3-D road condition profiles on the surface and underneath the surface. The performance of our innovative system is not the visual inspection, fiber/stress sensor, CCD, DCP, FWD, BB, laser ultrasonic and HRWD can achieve. The significance of our work is obviously there.

Table 2. Deflection Measurement Devices - Capabilities and Limitations (Arora, 2006)

Device Parameter	RDD	ARWD	HRWD	RDT	TSD	FNCNPES
Manufacturer	UT Austin	Dynatest and Quest	Applied Research Associates	VTI, Swedish National Rd Administra.	Green-wood Engineer.	EYZtek, Dayton, Ohio.
Estimated Cost	N/A	N/A	\$1.5M	N/A	\$2.4M	\$0.28M
Operation Speed	1 mph	20 mph	45-65 mph	60 mph	50 mph	up to 70 mph
Distance between readings	2-3 ft	1 ft	0.5 in	0.001 s	0.80 in.	0.00025 s
Applied Load	5 kips dynam.	9 kips	18 kips fixed	8 to 14 kips (40-70 kN)	11 kips (49 kN)	20 kips Hwy
Sensor Accuracy	100 µm	N/A	70 µm	256 µm	100 µm	70 µm

System Accuracy	N/A	1 mil at 6 mph	N/A	N/A	75 μm	60 μm
Other devices	GPS	N/A	GPS	N/A	GPS	GPS, GPR, encoder, etc.
Operators	2	2	2	2	2	2
Calibration	Yes	N/A	Yes	Yes	Yes	Yes
Basin measurement	N/A	N/A	N/A	N/A	N/A	Yes
Measure modulus, stiffness and other properties	N/A	N/A	N/A	N/A	N/A	Yes
Theoretical basis for results interpretation	N/A	N/A	N/A	N/A	N/A	Yes

4. Novel System Design

The novel device, **FNCNPNPES** consists of 3 subsystems, the first one is SRWD, the second one is RLSD, and the third one is GPR. Fig. 1 shows the top view of the FNCNPNPES design.

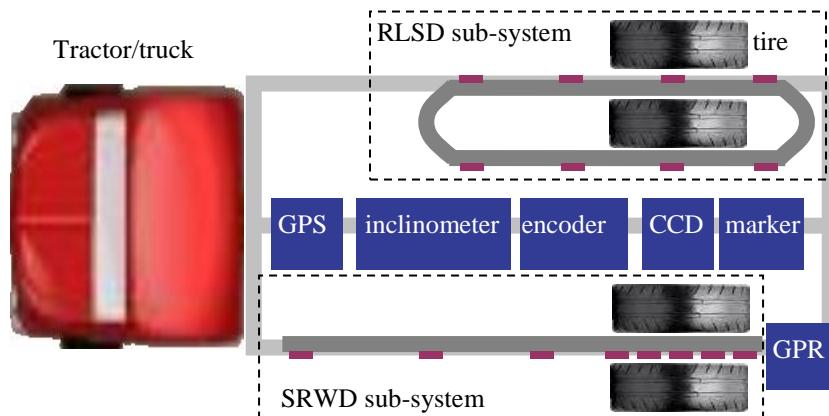


Fig. 1. Top view of the FNCNPNPES

In order to distinguish the heavy or long rolling weight deflectometer of 53' we use the word of short rolling weight deflectometer (SRWD) for the 24' short trailer. We will remodel the 24' gooseneck trailer. Because the trailer is short it can be towed by a F250 truck or other normal trucks. Any body can drive the truck and tow the trailer that gives us a great convenience for road test. The system also will include a CCD camera for surface condition survey, a GPS to know the locations, a speedometer or encoder to record the distances, an inclinometer to measure the road elevation, and a ground marker to mark the defects locations. Using the data from above sensors we are able to get the 3-D road condition profile with geographic coordinates. At the same time we also will derive a set of equations to use the thickness, deflection and basin to calculate the pavement modulus, stiffness, strength and other properties.

4.1. Short rolling weight deflectometer design

On one side of the trailer, eight displacement lasers will be assembled on a beam between the two tires as shown in Fig. 2.

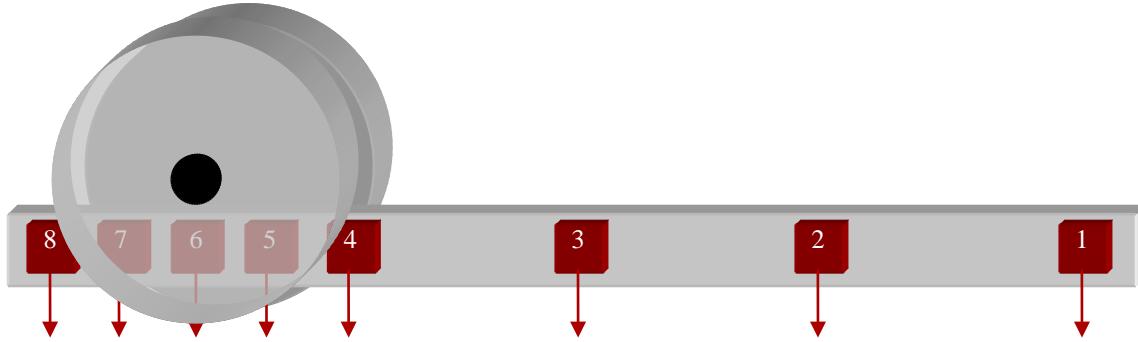


Fig. 2. Short Rolling Weight Deflectometer

The 1st, 2nd and 3rd lasers are placed 12-ft, 9-ft and 6-ft away from the axle, respectively. They are in the un-deflected area since the basin radius is only about 4 ft. The function of these three lasers is to measure the road surface level and the tilt angle of the laser mounting beam. The 4th to 8th lasers are placed in the deflected area. The 6th laser is placed directly under the axle and in between the tires, which gives the maximum deflection. The other lasers are placed on both sides symmetrically to measure the full basin. We may place four lasers on one side of the 6th laser to measure the half basin. Our experience shows that the basin extent is about 8 feet under 20,000 lb of load per axel, so the spacing between lasers is about 2 feet for full basin measurement or 1 foot for half basin measurement.

The system needs calibration for laser mounting. Firstly, we will put a 13-ft long sink under the eight lasers and pull laser-non-penetration liquid in the sink (the laser will timely penetrate water, milk, juice, etc. so they are not good for calibration). After about 30 minutes the liquid surface will be absolutely flat. The readings H_1, H_2, \dots, H_8 of the eight lasers at this moment represent their vertically relative positions to the liquid surface including their mounting differences and the beam tilt factor. We can use the readings from lasers 1 and 3 (laser 2 is for verification purpose to see if line 1-2 is almost as same as line 1-3) to make a straight line and get the calibration tilt angle θ relative to the liquid surface. After we get the relative positions of the eight lasers, we are ready to pull the trailer to the test road and collect the test data. The readings of eight lasers to the ground are obtained synchronously which include the same mounting differences, the new beam tilt angle caused by trailer vibration, the difference between the liquid level and the ground level, and the road surface unevenness. The same mounting differences can be subtracted from the test readings and the calibration readings. We can use the lasers 1 and 3 at the un-deflected area to get the tilt angle ϕ during the test.

For the road roughness, since the data acquisition rate is 4 kHz, even if the trailer's speed is 70 mph, we still can obtain a set of data every 7-8 millimeters. We can use data averaging and proper filtering in certain distance (or time) to remove the road unevenness or roughness because the average of positive and negative surface variations will be zero. The calibration procedure is shown in Fig. 3. From the diagram we can get the equations of the laser mounting positions during the lab calibration and road test. Because of the page limit, we will not give the detailed equations for the laser mounting differences but skilled readers can do by themselves after they have our clear diagram shown in Fig. 3. For simplicity, in the diagram we only use 7 lasers not 8 lasers. We use laser 1 and laser 2 at the non-deflected area to make a straight line.

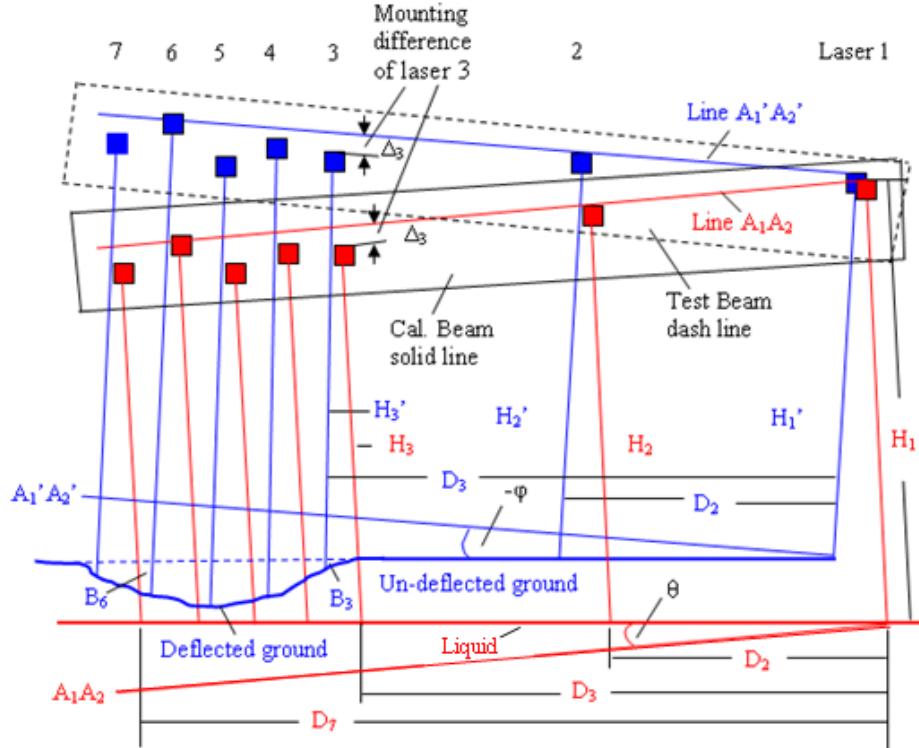


Fig. 3. Geometry of laser mounting on beam during calibration (red) and road test (blue)

In order to verify the correctness of the SRWD design, during the Phase-II contract with the AF, we built the prototype shown in Fig. 4_a and measured the highway deflection basin shown in Fig. 4_b. The curve of deflection basin is not smooth because the half basin only has 5 points. Therefore we designed and will produce the rotary laser slide deflectometer for dynamic basin measurement that can get hundreds points per basin.



Fig. 4_a. Eight lasers are mounted on the beam

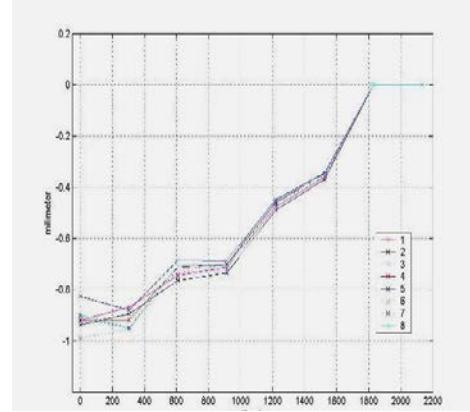


Fig. 4_b. Deflection basin of the highway

4.2. Rotary laser slide deflectometer design

In this sub-system, 8 lasers with equal spacing D are fixed on a moving belt between two rear tires as shown in Fig. 5 (also in Fig. 1). The driving shaft of the belt has a proper gear linked with the axle of the trailer, so the 8 lasers will move at the same speed v as the trailer but in the opposite direction.

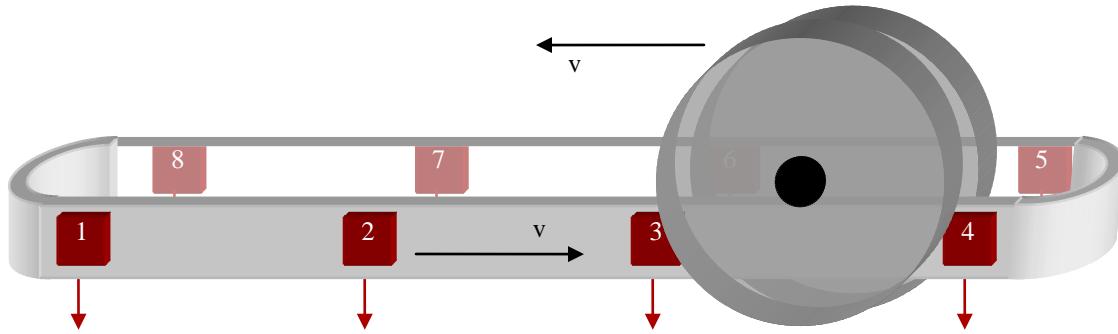


Fig. 5. Rotary laser slide deflectometer design

Therefore, when each one of the lasers is on one side of the rotary belt, the laser aims at the same spot on the ground until the laser is rotated to another side of the belt. This is illustrated in Fig. 6.

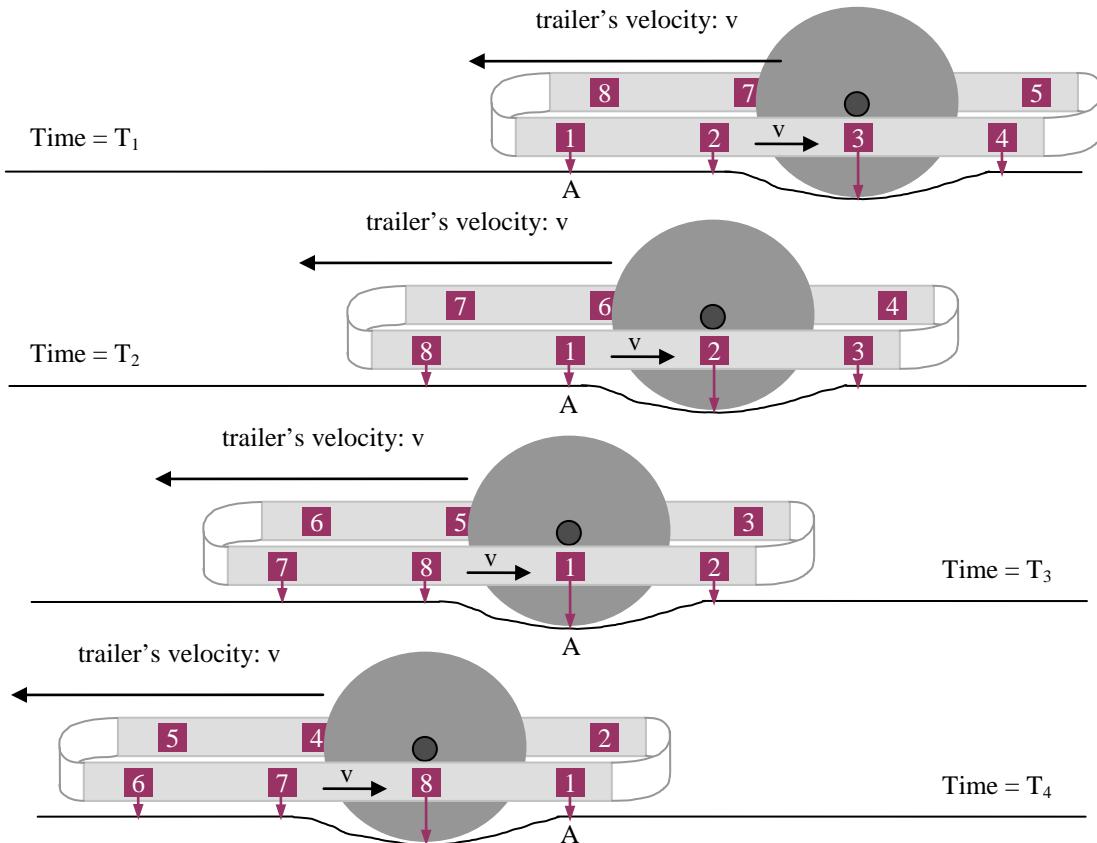


Fig. 6. Measurement procedure of the rotary laser slide deflectometer

In Fig. 6, at time T_1 , laser 1 shoots at point A on the ground. At time T_2 , the trailer moved forward but the rotary belt moved to the opposite direction with the same speed, so the laser 1 still shoots the same point A on the ground. At time T_3 , for the same reason, the laser 1 still shoots at point A on the ground, but at this time, the reading value of laser 1 contains the deflection basin value. At time T_4 , the laser 1 still shoots at the point A with no deflection basin. After time T_4 , laser 1 will be rotated to the other side of the belt and it will shoot at a different point on the ground. From Fig. 6, we can see that from time T_1 to T_4 , as long as laser 1 is on the

same side of the belt, laser 1 is always shooting at the same point A on the ground. Meanwhile, the whole deflection basin moves and passes through the point A. Therefore, the readings of laser 1 contain the deflection basin with hundreds of points. However, there is also an error contained in these values, which is that during this time period, laser 1 may move up and down with the trailer. The reading values of laser 1 contain not only the deflection basin but also the vertical movement errors. To solve this problem, at anytime of the test period, there are always at least two lasers aiming at un-deflected area as shown in Fig. 6. The values of these two lasers give us the ground level and the tilt angle of the beam. These values will be used to remove the vertical movement errors using the same method as discussed in paragraph 4.1. Therefore, using this innovative and unique design, dynamic basin with hundreds points (not 5 points) can be measured continuously with high accuracy and there is no problem from the road unevenness or roughness because the laser always aims to the same ground point.

To build the rotary laser slide needs time and money, instead we built a non-rotational laser slide for static basin measurement to verify the correctness of the RLSD working principle. The static basin is very useful because only the static basin can identify the surface deformation recovery status changing with time. For example, if the pavement basin cannot return to the original shape after the load is removed, the pavement has problems. Fig. 7_a is the linear laser slide with 1 scanning laser. During the demonstration, the laser slide is placed between two tires of the trailer parked on a street in the front of our company. The laser scans the road surface when the tire load is on; then, the truck tows away the trailer and the laser scans the ground again several times until the ground returns to the original shape. By using subtraction, a good static basin with hundreds of points is obtained (Fig. 7_b). Since the slide is fixed at the same location calibration is not necessary to make for slide bending/tilting/mounting compensation. The road roughness also will not affect the static basin curve because the slide scans the same road surface and subtraction will eliminate the effect automatically. As shown in Fig. 7_b, the lowest point occurs at coordinate (1.25m, 0.187mm). The number 0.187 mm (187 μ) indicates the deepest point of the basin (because the load is only 12,000 lb, the basin is not deep). Before this measurement, we used a laser level device D600 to measure the deepest point of the same basin and the result is 0.182mm. There is only 5 μ m discrepancy so the data obtained by the laser slide is highly accurate.

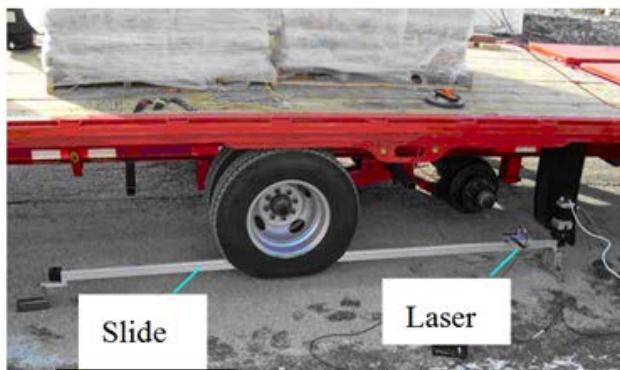


Fig. 7_a. Laser slide for road static basin measurement

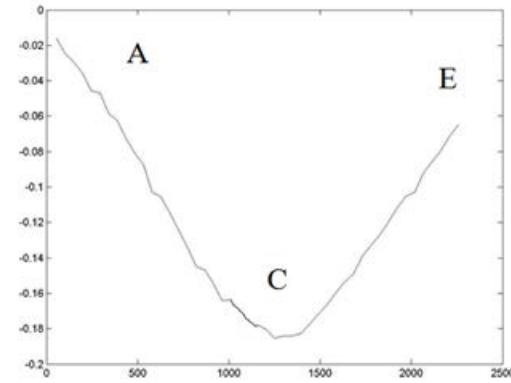


Fig. 7_b. Static deflection basin of the road

Fig. 8(a) shows the surface shape change at time t_1 and time t_2 ($>t_1$) when the load is applied on the pavement. At time t_n , the change will reach the maximum. Fig. 8(b) shows the surface shape change at time t_6 , t_7 and t_8 ($t_8 >t_7 >t_6$) once the truck is driven away. At time t_m , the change will reach the minimum and return to the original flat shape. By subtracting the shape at t_n from the shapes at t_6 , t_7 , t_8 , until t_m , decompressing basins changing with time can be obtained. By

subtracting the shape at t_m from the shapes at $t_1, t_2, t_3, \dots, t_n$, compressing basins can be obtained. The subtraction from t_m and t_n will yield the maximum static basin. Fig. 8(c) is the slope of the decompressing basins of a road. Obviously, at points A_1 and C_1 the basins have largest slopes and at point B_1 the basins have smallest slopes. Figs 9(a), 9(b) and 9(c) are the compression basins, decompressing basins and slopes calculated from deflection measurement at a parking lot. The slop curve will be very useful for the calculations of pavement modulus, stiffness, strength and other properties using the derived equations to be mentioned later.

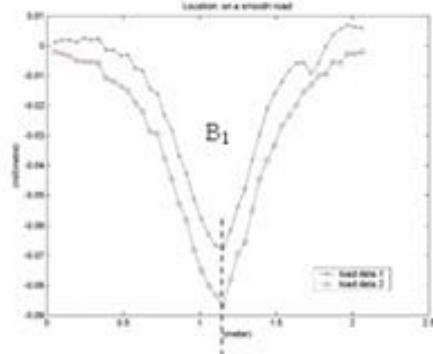


Fig. 8(a), Load on

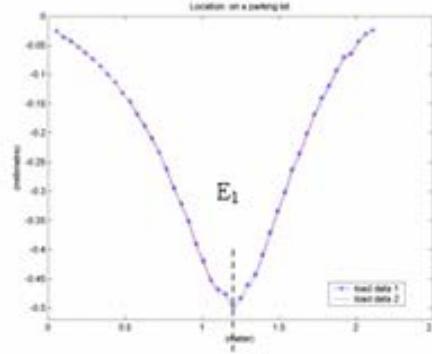


Fig. 9(a), Load on

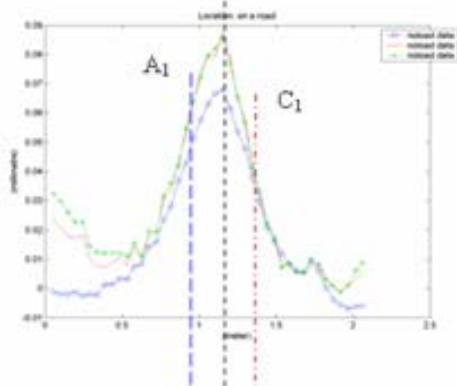


Fig. 8(b), Load off

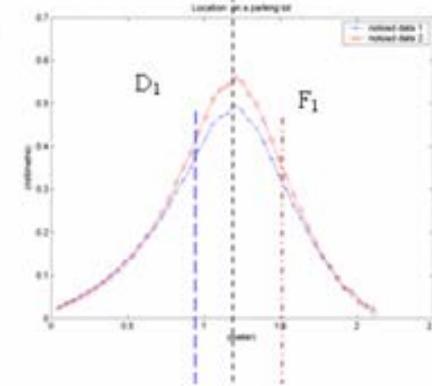


Fig. 9(b), Load off

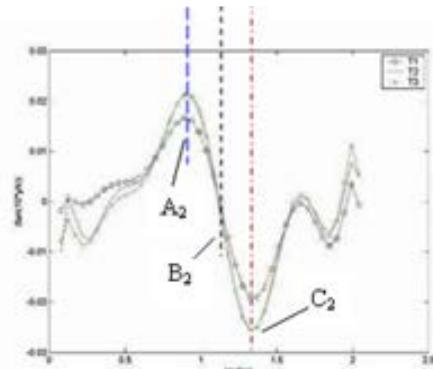


Fig. 8(c), Decom. basin slope of a road

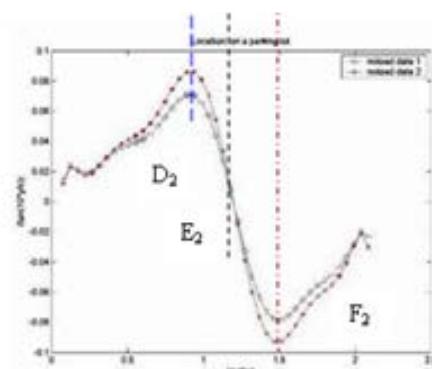


Fig. 9(c), Decom. basin slope of a parking lot

4.3. Road Hardness Test Results

In order to compare the road hardness we tested 6 roads. Road 1 is a local road inside a residential area, the pavement should be soft. Road 2 is a state road SR-747, it should be harder than Road 1.

Road 3 is a bypass interstate highway I-275, it should be harder than SR-747. Road 4 is another local road, pretty new, at the exit of I-275, it should be little harder than road 1 but softer than other highways. Road 5 is the interstate highway I-75, it should be the hardest one. Road 6 is a short interstate highway I-71, it should be softer than I-75. We measured the road deflections at the basin area from laser 6 and laser 7 to see if they have differences, if they have differences that should be the basin of two points at lasers 6 and 7. Table 3 lists the Mean Basin Value for laser 6 and laser 7. Obviously they are coincident with the true road conditions. We did not use laser 8 at the location between two tires because at the test time the short range laser 8 was broken.

Table 3. Road hardness measurement results (unit: μm)

	Road 1	Road 2	Road 3	Road 4	Road 5	Road 6
Laser 7	190	176	84	111	66	83
Laser 8	390	315	241	250	170	208

5. Equations for Pavement Property Calculation

As we pointed out before, to borrow the software from FWD to calculate the pavement property using ARA's HRWD data is not proper because the FWD can roughly get the discrete basins but HRWD cannot measure the basin at all. Although we have the basin and probably we can use the FWD software, since the basin measurements are different the best way is to develop our own equations and software. The equations derived using the concept of beams on elastic foundation can be used to calculate the pavement properties. The required data for the calculation are the pavement thickness from GPR and the deflection basin from SRWD/RLSD. The general equation of the deflected shape (y) under a concentrated load P is:

$$y = e^{qx} [C_1 \cos(qx) + C_2 \sin(qx)] + e^{-qx} [C_3 \cos(qx) + C_4 \sin(qx)] \quad (1)$$

Where, C_1 , C_2 , C_3 , and C_4 are integration constants that can be determined by considering continuity of the pavement. Once integration constants are determined, equation of deflected basin profile and the slope of the basin can be written as follows:

$$y = (Pq/2k) e^{-qx} [\cos(qx) + \sin(qx)] \quad (2)$$

$$\frac{dy}{dx} = \theta = - (Pq^2/k) e^{-qx} \sin(qx) \quad (3)$$

From Eqs 2 and 3 we can see that modulus of subgrade reaction (k) thus flexural rigidity (EI) can be calculated only if we can establish the point where deflection is zero ($y=0$) and we have the slope at that point (see Fig. 8). Further, modulus of elasticity of the pavement material (E) can be calculated knowing the thickness of the pavement to calculate moment of inertia of the section (I) or vice versa. Where,

$$q = (k/4EI)^{1/4} \quad (4)$$

q is characteristic factor. In above equations, the definitions of parameters are:

k = subgrade modulus of reaction

E = pavement modulus

I = moment of inertia of pavement

P = applied force

y = deflection

θ = deflection slope

Pavement thickness can be measured from GPR in-situ. Stiffness of the pavement can be calculated knowing pavement thickness and modulus, and California Bearing Ratio (CBR) or strength can be estimated using empirical relationships. The system capabilities are not available with any of the systems currently available in the world (see Table 2).

6. Expected 3-D Road Condition Profile

The SRWD/RLSD will measure the deflection and basin of the pavement, the GPR will measure the pavement thickness and visualize the defects (void, slit, water, disintegration, etc.) with depth underneath the pavement, by combining the data from SRWD/RLSD and GPR (see Fig. 10) with

highway speed and using the derived equations, the pavement modulus, stiffness, strength and other properties can be obtained; the GPS will show the defects locations, the speedometer or encoder will record the distance of the measured points, and the inclinometer will indicate the elevation of the road; by measuring the road back and forth (or lane by lane) several times, a 3-D road condition/defects profile underneath the pavement can be established. At the same time, the stereo CCD camera can record and display the surface defects in 3-D. Therefore, both 3-D road condition profiles above the surface and underneath the surface can be obtained, and the ground marker will mark the defects or weak road locations to let engineers and workers pay attention. Fig. 11 is the simulated 3-D road condition profiles on the surface and underneath the surface. If we can get this kind very useful 3-D road condition profile it will be the first one in the world.

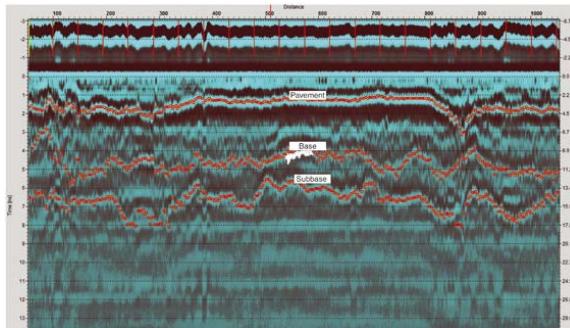


Fig. 10. Processed GPR data for pavement thickness measurement and defects detection

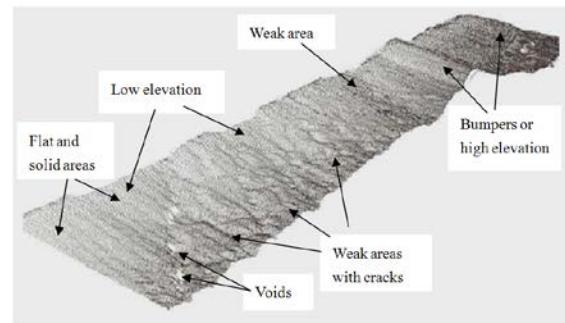


Fig. 11. 3-D road condition profiles on the surface and underneath the surface

7. Anticipated Benefits

The United State of America has 4,000,000 miles of public roadways, 600,000 bridges, and 15,000 airports. More than 50 percent of urban roads were in poor or mediocre condition. The nation's critical and urgent need is a new device that utilizes *Advanced Sensing Technologies and Procedures* to quickly evaluate pavement conditions on the surface and underneath the surface for the entire road network with traffic speed, the anticipated benefits of our FNCPNPES will be:

- (1) Can quantitatively measure highway, runway, road and bridge network performance with traffic speed up to 70 MPH..
- (2) Not disturb the traffic and can ensure the public safety.
- (3) Can develop a carefully planned and proactive pavement management program to improve the accuracy of prioritizing and targeting fund for the road segments that needs repairing, rehabilitation, or replacement.
- (4) If the existing pavements can be maintained in good condition, it can reduce the requirements of major rehabilitation or reconstruction work to save taxpayer money. The labor and time savings will be more than the material saving.
- (5) Can mitigate congestion to save taxpayers money, they spend more than \$78 billion per year.
- (6) Can save motorists money in repairs and operating costs, they spend \$67 billion per year caused by poor road condition.
- (7) Can keep highway, bridge, roadway and runway in good condition that is strategically important for our nation's defense and economy.

8. Reference

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3. Alan Zhang, et al, "Remote runway survey robot", **Phase-II final report to the SOF**, December 2004.