Development and Use of a Laser-Based Roadway Clearance Measurement System

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ABSTRACT

The Federal Highway Administration (FHWA) requires each state to maintain an accurate record of roadway clearances on all routes. Obtaining the vertical clearances can be particularly difficult on highways carrying high traffic volumes such as Interstate 25, a major North-South route through the heart of Denver.

In the past, the Colorado Department of Transportation (CDOT), like other agencies, measured these clearances manually with telescoping rods. In the most congested corridors, this method required lane and/or road closures. It also required personnel to be physically out on the roadway subjecting them to hazards from unaware drivers. In the metropolitan areas, the operation was usually performed at night when traffic volumes were lower, raising even more safety concerns because of the difficulty for vehicle drivers to see the personnel on, or near, the roadway in the dark.

Through an agreement with Bridge Diagnostics, Inc. (BDI) of Boulder, Colorado, a laser-based device and associated software were developed to measure vertical clearances while in motion. By combining laser and ultrasonic technology, the system measures and records the clearances, eliminates most of the safety concerns of personnel being out on the roadway, provides more accurate measurements, and requires significantly fewer resources to collect the clearance data.

This paper will discuss the development of the system, the accuracy of the results, some of the unanticipated problems that were encountered, and the procedures developed by CDOT to record clearances along their most heavily traveled routes.

INTRODUCTION

The Federal Highway Administration (FHWA) requires that the overhead clearances for structures over any traveled way must be measured and reported to the National Bridge Inspection Standards (NBIS). Colorado has approximately 3900 bridges on the state highway system. Of these, approximately 1400 (36%) have vertical restrictions and many are along highly congested routes in metropolitan areas.

Taking vertical clearance measurements in metropolitan areas can be a hair-raising challenge. Even at night, when traffic volumes are lower, bridge inspectors returned from a night's work commenting about the "close calls" that they experienced. It seemed that no amount of traffic control measures were enough to keep drivers from encroaching on the work areas.

In the early ninety's, the CDOT made attempts at measuring clearances using ground penetrating radar in an inverted mode. This idea was quickly abandoned because the readings were not repeatable (they were off by as much as 50.8 mm (2 in.) for multiple passes). More accurate antennas were available but the cost for these antennas was very high and the results had not been proven. Further attempts at an automated system were abandoned awaiting future developments in technology.

After completing the manual readings along Interstate 25 (I-25) in 1994 and experiencing more very "close calls," another search for an automated system was done. Again, an "off the shelf" system was not found. BDI suggested a laser ranging device and showed that they could provide an instrument with the necessary accuracy.

MANUAL CLEARANCE RECORDING IN METROPOLITAN AREAS

The most important aspect of taking manual readings can be the safety of personnel. Traffic control during these measurements can be quite extensive, even to closing entire roadways such as ramps. The traffic control plans for taking readings manually incorporated the use of impact attenuating trucks, flagging personnel, moveable message boards, directional arrow boards, and warning signs.

Coordinating the work required interaction with maintenance sections, law enforcement officials, entertainment venues (to avoid doing the work during events conducted at the various sporting and entertainment venues), and oversize/overweight permit offices. Scheduling enough personnel to do the work as quickly as possible and get off the road required the recruitment of volunteer office staff to be notekeepers and spotters.

All told, seventeen (17) people and seven (7) vehicles were required to manually measure the clearances of thirty-three (33) structures along a 32.2 km (20 mile) segment of I-25. The fieldwork took a total of sixteen (16) hours over two nights. To add to the complexity, two law enforcement agencies were involved and adjustments had to be made to accommodate their separate requirements each time that the seven-vehicle caravan crossed the agency boundaries.

During the time that the measurements were actually taken, maintaining a plumb rod, being sure it was in contact with the girder being measured, all while reading the scale as traffic "whizzed by" can test the most hardened inspector. Wind is also a factor affecting accuracy because the rod can bow or lose contact with the girder just as the inspector looks down to read the scale. The accuracy of some readings taken under these conditions can be questionable.

DEVELOPMENT OF THE AUTOMATED SYSTEM

After the 1994 manual effort, the CDOT entered into an agreement with BDI to develop a turnkey automated system meeting the following CDOT requirements:

- An overall measurement accuracy of ± 13 mm (± 0.5 in.),
- An overall accuracy rate of 95%,
- The unit must be powered by a 12 VDC source (car battery),
- The system must be capable of operation during daylight hours,
- The measurements must be vertical,
- The system must be capable of taking readings while the vehicle is in motion,

- The system must record, and store, the readings electronically,
- The unit must be a complete system capable of taking the readings, analyzing the data, and presenting the results.

The system that was developed is made up of three major components:

1. The laser/ultrasound distance sensors combined into a single unit,
2. The "black box" signal processor, and
3. The laptop computer which controls all functions of the system including on /off.

DISTANCE SENSORS

The "up" measurement is taken with a Class IIIa Modulated-Beam ranging laser. The laser has an accuracy of 10 mm over an 8 m range and a sampling rate of 140 Hz. This particular laser was selected because it is capable of sensing return signals from a passive target (no reflector or reflective material is required to return the signal). In fact, a return signal from a shiny surface is not readable. The laser is *not* eye safe and caution should be exercised when the laser is on. A flashing warning light is activated automatically, and remains flashing while the laser is on.

Since the vehicle on which the unit is mounted could potentially bounce as it travels under a structure and lead to erroneous data, it was decided that a "down" measurement is required as well. The down measurement is taken using an ultrasonic ranging device which has an echo range of 305 mm (12 in.) with an accuracy of 2 mm (0.08 in.) and a sampling rate of 70 Hz. This system, then, provides a total measurement from the ground to the girder and makes the instrument independent of what is happening to the vehicle. It is also an economical compromise to using two lasers.

The laser has a built-in heating element and is relatively immune to ambient temperature variations. The ultrasonic ranging device, on the other hand, is susceptible to temperature and humidity variations. To compensate for these atmospheric variations, a second ultrasonic sensor is mounted as a reference. A target for the reference sensor is mounted at a fixed distance and the reference signal is sampled as well as the return from the ground to the primary sensor. The speed of sound is calculated for the prevailing weather conditions based on the response from the reference and used to ratio the output of the "down" sensor.

The unit cannot be used in rain, mist, or snow because the signals will be scattered by moisture droplets. Even wet roads can produce a mist that would affect the sensors. Therefore, the unit should only be used during times of good weather. The ambient temperature also affects the unit. Through testing, it was determined that the optimum ambient temperature ranges between 4°C (40°F) and 35°C (95°F). In addition, the unit cannot be exposed to direct overhead sunlight, which can damage the photodetector.

SPEED OF VEHICLE CAN AFFECT RESULTS

The CDOT limited the speed of the vehicle to 8 kph (5 mph) while taking the readings under multiple-girder structures. This provided a sufficient number of samples, 0.63 samples/cm (1.59 samples/in.), to determine a measurement from narrow girders within the required tolerance. For structures with very wide bottom flanges, such as box girder structures, the speed can be increased, but that is of little benefit when compared to the overall time involved in taking the measurements.

Slower travel rates produce results that are much more precise, but the volume of data, because of the slower speed, became unmanageable using the computing capabilities at the time the instrument was developed. It is also necessary to allow enough time for the data to be sent from the signal processor to the laptop computer via the serial port before beginning a new structure. The volume of data, then, also affects the time required for transfer. Generally, this transfer requires no more than one minute but, during this time, no readings can be taken. These factors are both dependent on computing capabilities but, as computing power continues to improve, they will be less of a consideration.

MECHANICAL COMPONENTS

The unit is mounted to the front of a vehicle using a specially constructed bracket that is clamped to the front bumper. The bracket allows the unit to be placed on either the left side or right side of the vehicle. It is easily switched from one side to the other when necessary.

A shroud is provided around the unit for general protection from sun, wind and debris. This shroud also helps to reduce temperature changes as the van travels between bridges.

A swiveling device and a counterweight are used to keep the instrument vertical. To keep it from swinging freely as the van travels down the road, the swiveling system uses a built-in damper, a miniature version of a shock absorber.

After initial use of the system, the CDOT found that even at the recommended speed it was somewhat difficult to keep the instrument directly above a lane line while taking the readings. To aid the driver in keeping the instrument over a line, the CDOT installed a video system used in many of today's large motor homes. The video system includes a miniature video camera that was mounted to the front of the instrument's wind shroud and a small monitor that was mounted to the dashboard near the driver. Markings were placed on the monitor's screen to give the driver a sight to keep the unit over the selected line. This system worked very well.

ELECTRICAL REQUIREMENTS

The unit and all of the accessories, except the laptop computer, are connected directly to the vehicle's 12 VDC battery via cabling enclosed in a harness. The laptop was connected through the cigarette lighter. The CDOT set up the connectors on the harness, and the ones to the battery, so that they could not be interchanged. This was a lesson learned the hard way when the positive (+) and negative (–) leads were inadvertently swapped once.

The electrical connections, which are now protected by fuses, bypass the ignition switch so that the laser can remain at operating temperature even when the ignition switch is turned off. This is necessary so that, during breaks in the work, the laser will remain at operating temperature and the crew can avoid having to wait for it to warm up to restart.

From a “cold” start, the laser can take up to thirty (30) minutes to warm up depending on the ambient temperature.

SOFTWARE

The entire operation of the unit is controlled from the laptop computer. A menu-driven custom program allows the user to switch the unit on and off, monitor all instrument functions in real time, create bridge files, and store the data for each pass. The software is flexible enough for the operator to make changes or corrections in the setup strings quickly. The original signal processing software was DOS® based. The data reduction and plotting program is a Windows® application.

The software also plots the results of the measurements. This plot results in a reproduction of the structure cross-section along each line. A table is also produced listing every clearance that was measured and the minimum clearance along each of the lines under the bridge. Future envisioned improvements include a seamless integration with the Pontis Bridge Management System so that data from the instrument will automatically update clearance information for each bridge measured.

FIELD OPERATIONS FOR AUTOMATED CLEARANCE MEASUREMENTS

In contrast to the manual measurement effort described earlier, the field team for the automated clearance measurements was comprised of only two inspectors in one van followed by one maintenance worker driving an impact attenuating truck with an arrow board as the sole means of traffic control. This small caravan took the measurements while in motion, thereby minimizing the effect on the traveling public. A cost comparison of an earlier manual effort versus the automated system is shown in Table 5.

Structures along C-470, a perimeter highway around Denver, were used to familiarize the crew with the instruments and the procedures. The highway had a low ADT and several representative structures. This is where much of the final procedures were established. Once the crew was comfortable with all of the processes, I-25 through the heart of Denver was scheduled. That section of I-25 had recently undergone an overlay and the clearances needed to be updated.

Approaching each structure, the caravan slowed to take the readings. The caravan accelerated to about the posted speed limits between structures. The system takes readings for only one lane line at a time. So, multiple passes are required to complete the measurements for each line under each structure. To avoid backing up and moving over for each lane line, the CDOT found that the most efficient way to keep the operation moving was to plan loops within highway segments.

Each loop was comprised of several passes under successive structures bounded by convenient turn around points. One lane line was measured during each pass. For each succeeding pass, the vehicle was moved to the next lane line. This process was continued until all of the lane lines and shoulder lines under each of the structures in the loop were completed. Then, the entire process was repeated for the next loop.

Factors considered when establishing these loops included the length of each segment, the distance between structures, and the location of turnaround points. The

CDOT found that 8-kilometer (5-mile) stretches were about the maximum efficient lengths for each loop. The distance between structures also influenced the establishment of the loops. It can be more efficient to have two, or more, shorter loops rather than one long loop with considerable "dead time" (long distances) between structures.

The computer files for the loops were pre-arranged in the PC so that each file could be brought up in the same order as the bridge and lane line that is to be measured. If a mistake was made, however, the software was flexible enough to make corrections easily "on the fly."

Prior to beginning the fieldwork, the bridge inspection team should be allowed time to define each loop accurately and to set up the appropriate computer files. The CDOT team set up the loops by traveling the highway and taking notes at each structure to be measured. In addition to establishing the loops, they made a "dry" run to be sure that the plan was accurate. The time spent in planning the work is more than recouped by efficiency and safety in the operation and timely completion of the measurements.

Before the work got under way, the bridge inspection team and the maintenance driver discussed the plan. In this way, the maintenance driver was generally aware of what to expect as the work progressed. The maintenance truck and the inspection van were in communication via two-way radio to ensure that each knew what the other was doing, or was about to do. This was especially important when unforeseen changes in plans became necessary or when traffic volumes required the crew to stop for a few moments.

When the measurements are in progress under a bridge, the recommended speed of the van is 8 kph (5 mph). Between bridges, the van can travel at the posted speed limits. However, the temperature of the outside air should be considered so that the speed of the van doesn't cause the temperature of the laser to fall greatly below the optimum of 35°C (95°F). If it does, the laser's temperature should be allowed to return to optimum before starting readings on the next structure. The temperature of the laser can be monitored from the laptop.

The time of day is also a factor affecting accurate measurements. During testing of the unit, the CDOT found that readings should not be taken when the sun is high in the sky (eleven o'clock to one o'clock standard time) because the sun causes erratic results. In fact, the sun shining directly on the focusing mirrors can damage the electronics in the laser.

COMPARISONS OF MEASUREMENTS (MANUAL VERSUS AUTOMATED)

The original test results are shown in Tables 1, 2, and 3 below. These tests were conducted on Interstate 70 at a location where there are three adjacent parallel structures of different

Table 1: Multiple Passes Under Concrete Box Girder Bridge (clearances in meters)

Location	Pass 1	Pass 2	Pass 3	Pass 4	Pass 5	Rod	Max Diff.	Range of Unit
West * Edge	6.5270	6.4660	6.4630	6.4721	6.4691	6.4264	0.1006	0.0640
Center	6.6490	6.6399	6.6490	6.6521	6.6551	6.6402	0.0149	0.0153
East edge	6.6490	6.6368	6.6490	6.6460	6.6460	6.6466	0.0024	0.0122

*Readings on this edge of the box were affected by sunlight

Table 2: Multiple Passes Under Concrete Prestressed Girder Bridge

Girder	Pass 1	Pass 2	Pass 3	Pass 4	Pass 5	Rod	Max Diff.	Range of Unit
1	*	*	*	*	*	6.0238	*	*
2	*	*	*	*	*	6.1095	*	*
3	6.1732	6.1683	6.1619	6.1698	6.1683	6.1763	0.0031	0.0113
4	6.2144	6.2144	6.2113	6.2129	6.2144	6.2144	0.0000	0.0461
5	6.2589	6.2556	6.2525	6.2540	6.2556	6.2620	0.0030	0.0064
6	6.2986	6.2955	6.2906	6.2922	6.2906	6.2970	0.0015	0.0079
7	6.3510	6.3431	6.3416	6.3480	6.3446	6.3510	0.0000	0.0095
8	6.4605	6.4541	6.5624	6.5624	6.4541	6.4495	0.1128	0.1083
9	6.5194	6.5130	6.5130	6.5084	6.5130	6.5163	0.0031	0.0110
10	6.5560	6.5545	6.5511	6.5511	6.5545	6.5511	0.0049	0.0049
11	6.6130	6.6115	6.6100	6.6148	6.6148	6.6148	0.0000	0.0049

* The sun affected the readings for the exterior and first interior girders.

types, a concrete box girder, a concrete prestressed girder, and a welded plate girder. These tests were conducted prior to the installation of the video guidance system and were affected by the meandering of the truck.

COMPARISONS OF RESOURCE REQUIREMENTS (MANUAL VS. AUTOMATED)

The following tables (4 and 5) compare various aspects of the work to illustrate the difference between using telescoping rods and the automated system. CDOT had manually measured the clearances on a 20-mile segment of I-25 through Denver in 1994. The average traffic count for this section was approximately 150,000 vehicles per day. In 1998 a 36-mile segment was measured with the automated system and included the 20-mile segment manually measured in 1994.

As seen in Table 5 (next page), the costs are drastically reduced in just about every category. The one comparison that does not appear favorable is the comparison of time/bridge. This is because it takes more time to complete the "loops." But, it should be noted that most of this time is driving between bridges and the personnel are inside the vehicle.

Table 3: Multiple Passes Under Welded Plate Girder Bridge

Girder	Pass 1	Pass 2	Pass 3	Pass 4	Pass 5	Rod	Max Diff.	Range of Unit
1	*	*	*	*	*	6.3352	*	*
2**	6.3001	6.2955	6.3001	6.3001	6.2937	6.3257	0.0256	0.0064
3	6.2842	6.2891	6.2906	6.2876	6.2857	6.3001	0.0095	0.0064
4	6.2906	6.2876	6.2812	6.2891	6.2842	6.2876	0.0031	0.0095
5	6.2668	6.2668	6.2635	6.2668	6.2668	6.2717	0.0049	0.0034
6	6.2842	6.2812	6.2827	6.2842	6.2796	6.2876	0.0034	0.0046
7	6.2461	6.2415	6.2430	6.2397	6.2491	6.2461	0.0031	0.0095

* The sun affected the readings for this exterior girder.
** The rod reading for this girder was in error.

Table 4: Comparison of Resources Necessary for Manual vs. Automated Measurements

OPERATIONAL RESOURCES COMPARISON		
Category	**Manual System**	**Automated System**
# Personnel Required	17	3
# Vehicles Required	7	2
# Field Hours Required	16	40
# Person-Hours Required	270	120
# Girders Measured	318 (Selected Girders Only)	3049 (All Girders)
# Clearances Recorded	159	905

The initial cost of the instrument is not included in these comparisons. However, the numbers indicate that after only three or four uses, the system will have paid for itself in the cost savings.

The initial time used to set up the "loop" files is not included because it can be so variable. However, this only needs to be done once and the loops can be saved for future updates of the measurements.

QUALITATIVE COMPARISONS

Table 6 shows the qualitative comparison between the methods. Although it is difficult to quantify these factors, they are significant to the overall safety and accuracy of the work.

CONCLUSIONS

The safety of bridge inspectors became of paramount importance during the measurement of vertical clearances. As the Denver metropolitan area grew, and the volume of traffic on the highways in and around the metropolitan area increased, it was determined that an automated system was required to avoid a serious accident.

The automated system that was developed proved to be a viable, safer, and cost-effective means of collecting the data in congested metropolitan areas. The advantages to the automated system are:

- Fewer personnel are required,
- Minimal traffic control is required,

Table 5: Cost Comparison of Taking Manual vs. Automated Measurements

COST/PRODUCTIVITY COMPARISON		
Category	**Manual System**	**Automated System**
Total # of Bridges	33	52
Total Cost (1998 dollars)	$10,900	$2,900
Cost/Structure	$330	$56
Cost/girder	$34	$0.95
Cost/measured clearance	$68	$3
Time/bridge (min)	30	45
Person-hours/Bridge	8.2	2.3

Table 6: Qualitative Comparison of Taking Manual vs. Automated Measurements

OVERALL QUALITATIVE COMPARISON		
Criteria/Consideration	**Manual System**	**Automated System**
Initial Cost of Equipment and time for preparation.	Minimal	Significant: 1. Some modification to inspection van 2. Preparation of bridge file "loops".
Accuracy	Hurried effort, accuracy often questionable. Selective girders measured	±1/2 inch and repeatable. All girders are measured.
Data Format	Manually input results into BMS	Data imported into BMS via software
Safety	Personnel in roadway	No personnel in roadway
Traffic Control	Extensive traffic control devices and personnel throughout the work area	One impact attenuating truck w/ integrated arrow board

- Every girder gets measured and the clearance is listed,
- The software identifies the minimum clearance over each lane line,
- The measurements are accurate and repeatable,
- The overall cost per measurement is much lower,
- The unit is of moderate cost, and
- The system allows for future upgrades to the software to update the BMS clearance information automatically.

Some disadvantages of the system are:

- It is affected by direct sunlight and use should be avoided during the middle of the day,
- Improvements are necessary in the electrical connections to make handling of the wiring harness easier,
- More integration of the three units would be helpful to reduce the number of components.

Today, on rural, low volume highways, manual measurements are still used by the CDOT. However, as technology allows improvements to our current system, it is very probable that each inspection crew will be equipped with an automated unit for accuracy's sake, if nothing else.