ACCURATE AND PORTABLE WEIGH-IN-MOTION SYSTEM FOR MANIFESTING AIR CARGO*

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ABSTRACT

An automated and portable weigh-in-motion system has been developed at Oak Ridge National Laboratory for the purpose of manifesting cargo onto aircraft. The system has an accuracy range of ±3.0% to ±6.0% measuring gross vehicle weight and locating the center of balance of moving vehicles at speeds of 1 to 5 mph. This paper reviews the control/user interface system and weight determination algorithm developed to acquire, process, and interpret multiple sensor inputs. The development effort resulted in a self-zeroing, user-friendly system capable of weighing a wide range of vehicles in any random order. The control system is based on the STANDARD (STD) bus and incorporates custom-designed data acquisition and sensor fusion hardware controlled by a personal computer (PC) based single-board computer. The user interface is written in the "C" language to display number of axles, axle weight, axle spacing, gross weight, and center of balance. The weighing algorithm developed will function with any linear weight sensor and a set of four axle switches per sensor.

Keywords: portable weigh-in-motion, center of balance, shipment of vehicles, air cargo

1. INTRODUCTION

When the armed forces deploy wheeled vehicles by aircraft, each vehicle must be weighed and measured to determine the weight of individual axles, the gross vehicle weight, and the center of balance. The majority of the time this operation must be performed at sites where in-ground scales are not available. Presently, this operation is performed by using small portable scales, a calculator, and a tape measure. The scales are placed on the tarmac or other suitable surface, and the vehicle's wheels are driven up onto the scales. The readings from individual scales on the same axle are added together to obtain the axle weight, and the tape measure is used to measure the distance between the axles. The collected information is used to calculate the center of balance and the gross vehicle weight. In cases where weighing the vehicle requires more portable scales than are available, the process must be performed in steps since the scales must be moved from axle to axle. Different branches of the armed forces have expressed interest in developing technologies that will automate this vehicle data acquisition, subsequently expediting deployment of military units into and out of theaters of operation.

In partnership with the Tennessee Air National Guard, Oak Ridge National Laboratory (ORNL) has developed and tested an automated vehicle data acquisition system (AVDAC) that performs the above-described operation as vehicles drive over a set of sensors. The system has a usable range of 500 to 40,000 lb per axle (20,000 lb per sensor), from one to ten axles, and up to 50 feet separation between axles. The minimum spacing between axles is ~30 inches. The actual distance depends on the distance between the tire footprint of the leading wheel with respect to the trailing wheel of the closely spaced axles. That distance must be greater than 26 inches. To achieve the specified accuracy, the system must be operated in the speed range of 1 to 5 mph. The system will operate up to 19 mph with reduced accuracy. In the second phase of this project, a suitable vendor will be chosen to manufacture this system for the U.S. Air Force. The system will then be used to deploy military units and will be shipped with the units for use during the return deployment. The

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completed system described in this document was used in an actual deployment of an Air National Guard unit, reducing what normally would have taken 2 days to 2 hours.

1.1 Commercial system versus new development

Although commercial portable weigh-in-motion systems are available, these systems do not offer the accuracy required by the military, nor do they calculate the center of balance of a moving vehicle.[1-5] Researchers at the ORNL determined that accuracy of portable weigh-in-motion systems would be improved by using a weight determination algorithm that integrates the sensor output over time as the tire rolls over the sensor. A system that meets military requirements was developed by combining the weight sensors and ramps from a commercially available system with tape switches and custom-designed hardware/software. The resulting system produces in-motion weight readings with accuracies of ±3.0% with a 64% confidence level and ±6.0% at a 93% confidence level when weighing vehicles selected at random. The confidence levels were calculated using the data from 315 vehicle test runs.

1.2 Sources of error in weigh-in-motion systems

There are many sources of error in a weigh-in-motion system,[6] but the main source is from vehicle dynamics caused by suspension system oscillation, wind, and roadway conditions. This motion of the vehicle and suspension system is a source of error because it causes weight to be shifted from wheel to wheel and axle to axle as the vehicle moves. If the entire vehicle were at some point in time being measured by the weigh-in-motion system, the majority of error could be canceled out by reading the weight of all wheels at that instance. The effect of wind would still need to be corrected for by some other method. Of course, providing a sensor array system large enough to monitor all axles at once is not practical for a portable system. Portable weigh-in-motion systems such as AVDAC typically use one weight sensor per wheel path. With this arrangement, weight shifting from side to side on the same axle will tend to cancel out, but weight shifting from axle to axle can be missed in the measurement entirely. Suspension oscillation in the wheel being measured can be compensated for by integrating the weight samples over time. Axle-to-axle weight shifting can be minimized by using a ramp system before and after the weight sensors. The ramp system has a significant effect in reducing weight shifting on tandem axles such as found on the rear of semitrailers. The ramps must be long enough so that both axles are up on the ramps while weight measurements are being made.

1.3 Testing and calibrating the system

A special test facility was designed by ORNL and built by the Tennessee Air National Guard to test and calibrate the AVDAC. This facility provided a level, 100-feet-long concrete test bed with a sensor trough located at the center. The trough enabled the sensors to be placed flush and level with the roadbed while still being firmly supported from beneath. Placing the sensors flush and providing a long, level approach and exit minimizes perturbations to the test vehicle suspension. To determine the accuracy of the weigh-in-motion system, initial tests were performed with the sensors located in the trough. After the system was calibrated and a statistical database of tests obtained, the sensors were moved aboveground to the normal operating position and used with ramps. The set of tests was repeated to determine what effect moving the sensors aboveground had on accuracy. An accurate in-ground scale was installed at one end of the concrete test bed for the purpose of measuring test vehicle gross weight. Before each test, and at intervals during tests, the gross weight of vehicles under test was checked with the in-ground scale. An assortment of concrete slabs was available to load onto vehicles with a forklift to vary the test weight and center of balance.

The Air National Guard provided six military vehicles and experienced drivers to operate them. The vehicles were a 1- ton pickup, a humvee with a trailer, a three-axle 2.5-ton truck with dual rear tires, a three axle 5-ton truck, a four-axle tractor trailer, and a five-axle tractor trailer. Many hundreds of runs were made with these vehicles while varying the gross vehicle weight, tire pressure, center of balance, tire alignment to the sensors, and speed. The system was calibrated to give the best accuracy with only one calibration setting for all the vehicle types. The tests indicated that varying tire pressure and tire position on the weight sensor had little effect on the accuracy of the system. More consistent readings are obtained with the heavier, longer vehicles. This is attributed to the facts that the smaller vehicles have suspension dynamics that affect the weight readings more than the larger vehicles and that lighter loads are operating near one end of the sensor range. Tables 1 to 3 are results of the final aboveground tests using three different vehicles. These three vehicles represent a good cross section of the size, type, and weight of military vehicles that would be weighed by the system. The coefficient of variation is the standard deviation of the weights divided by the average weight and is a measure of the relative precision of the measurements.[7] The smaller coefficients of variation indicate a higher degree of precision. The term "Manual COB" refers to the center-of-balance calculation of the vehicle obtained by using the in-ground scale, a tape measure, and a hand-held calculator. The term "Dynamic COB" refers to the center of balance of the same vehicle as calculated by the weigh-in-motion system.

Table 1. Humvee with Trailer

	Light Load			Heavy Load		
	Average of Readings	Standard Deviation	Coefficient of Variation	Average of Readings	Standard Deviation	Coefficient of Variation
Static Scale Ref.	9,261.67 lb	38.46 lb	0.40 %	9,994.17 lb	35.73 lb	0.36%
4-6mph	9,199.83 lb	137.66 lb	1.50%	9,970.00 lb	141.25 lb	1.42%
2-3 mph	9,288.50 lb	141.86 lb	1.53%	9,931.33 lb	114.68 lb	1.34%
Manual COB	9.62 ft	0.014 lb	0.145%	10.53 ft	0.037 lb	0.353%
Dynamic COB	9.92 ft	0.142 lb	1.433 %	10.88 ft	0.140 lb	1.290%

Table 2. 2.5-Ton Truck

	Light Load			Heavy Load		
	Average of Readings	Standard Deviation	Coefficient of Variation	Average of Readings	Standard Deviation	Coefficient of Variation
Static Scale Ref.	14,416.70 lb	101.25 lb	0.70%	19,711.70 lb	109.66 lb	0.56%
4-6 mph	14,546.70 lb	250.12 lb	1.72%	19,975.60 lb	208.17 lb	1.15%
2-3 mph	14,485.10 lb	132.90 lb	0.92%	19,825.00 lb	265.92 lb	1.34%
Manual COB	6.99 ft	0.042 lb	0.605%	9.08 ft	0.011 lb	0.597%
Dynamic COB	7.18 ft	0.058 lb	0.804%	9.28 ft	0.094 lb	1.010%

Table 3. Tractor Trailer

	Light Load			Heavy Load		
	Average of Readings	Standard Deviation	Coefficient of Variation	Average of Readings	Standard Deviation.	Coefficient of Variation
Static Scale Ref.	33,752.50 lb	65.83 lb	0.20%	45,266.70 lb	64.08 lb	0.14%
4-6 mph	33,815.60 lb	448.00 lb	1.32%	45,511.30 lb	340.80 lb	0.75%
2-3 mph	34,100.90 lb	200.69 lb	0.59%	45,639.30 lb	310.85 lb	0.68%
Manual COB	24.78 ft	0.046 lb	0.187%	27.87 ft	0.064 lb	0.230%
Dynamic COB	25.04 ft	0.124 lb	0.495%	28.03 ft	0.130 lb	0.465%

2. DESCRIPTION OF HARDWARE

To measure vehicle parameters, the AVDAC uses a bending plate strain gauge weight sensor placed between two sets of tape switches. Tape switches are commercially available elongated pressure sensitive switches designed for traffic lane monitoring. The system pictorial diagram in Fig. 1 shows that one sensor assembly is used for each wheel path of vehicle traffic. The two sensor assemblies are connected to an electronic monitoring system (Fig. 2) that processes data from the sensors, interfaces to the operator, and prints out the vehicle data. The cable assemblies that connect the sensor units to the electronics are of sufficient length to remove the operator to a safe distance. The electronic monitoring hardware complies with the STD bus standard and consists of only three circuit boards. Two of these circuit boards are custom designed for the application and are identical to each other. They are referred to as the "wheel path data acquisition and time processing units" and have address decode select switches to allow multiple units on a single bus. The third board is a commercially available 486 PC single-board computer with solid state disk drives, printer port, two serial ports, disk controller, ram memory, video support, and resident operating system in programmable read-only memory. These circuit boards are installed in a STD bus backplane to comprise most of the electronics. The input device shown in Fig. 2 is a hand-held keypad used by the operator to send commands to the system. The keypad also contains a small backlighted display that provides current system status information to the operator. The output device is a compact printer that uses normal copy machine paper. A printer output device is required by the military because a weight and center-of-balance record must be produced and attached to each vehicle. An added advantage of the printer is that it functions under bright sunlight conditions. An optional color video graphics array (VGA) display can be attached to the

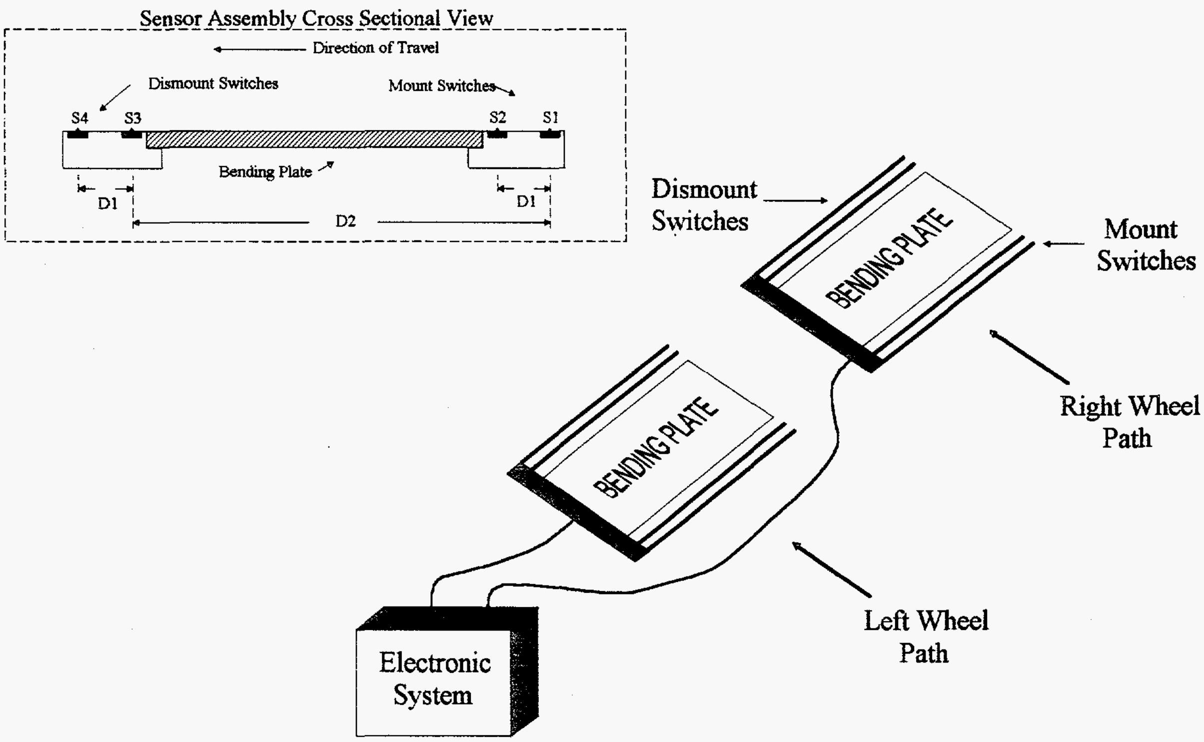

Fig. 1. System Pictorial Diagram

system. This display provides a graphic indication of the number of axles and center of balance of the last vehicle weighed. In addition to the graphics, the weight and spacing of the individual axles, the total vehicle weight, and the center of balance are displayed in text. Any VGA-compatible monitor can be connected to the system and operated in parallel with the printer when this type of output is desired.

2.1 Sensor assembly description

Referring to the sensor assembly cross-sectional view in Fig. 1, note that switches S1, S2, S3, and S4 are permanently fastened to the bending plate at predetermined distances from each other. These fixed distances, when combined with timing information, enable tire velocity calculation. The switches detect when a tire mounts and dismounts the bending plate and produce timing information related to tire movement and the length of tire contact with the roadway. The use of two switches preceding and two switches following the weight sensor reduces the probability that pad mount or dismount will fail to be detected on tires with large gaps between the treads. When only one switch is used, this condition exists when the switch aligns with a gap in the tread. The distance "D1" was chosen based on experience with aggressive tread tires and is effective in reducing the chance that gaps in tire treads will cause switches to be missed. The system will function normally when only one switch on either side of the weight sensor is activated, but the majority of the time all four switches are activated. The additional switch data are used to advantage by averaging them to improve the accuracy of the velocity and distance measurements. When the tire mount is detected, the output of the bending plate transducer is sampled at 4000 samples per second until the dismount is sensed.

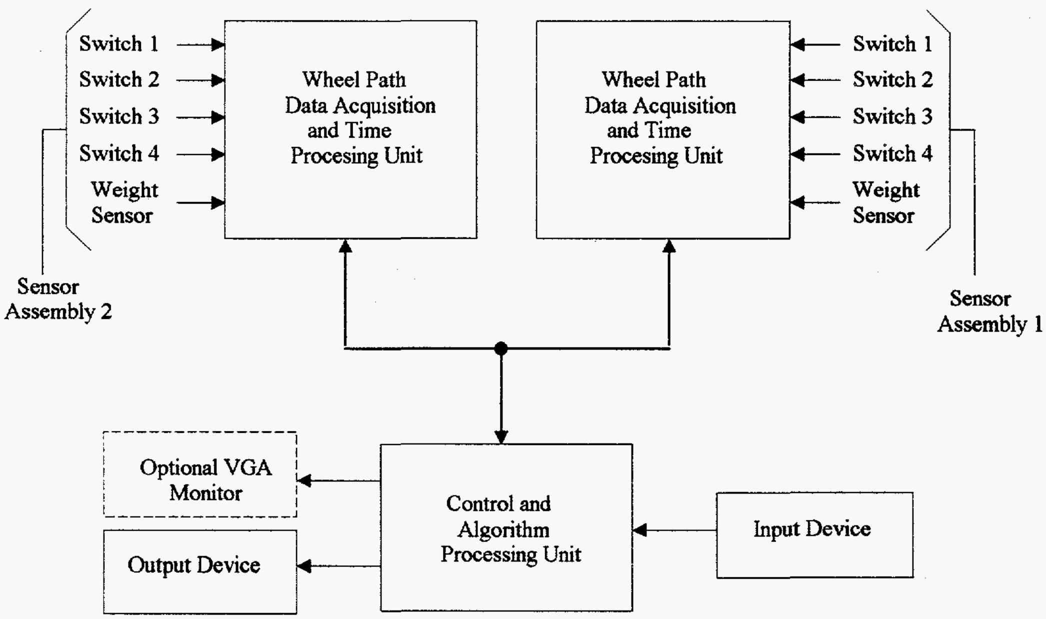

Fig. 2. Electronic Monitoring System

2.2 Wheel path processor description

Two identical wheel path data acquisition and time processing units are used to monitor and acquire data from the sensor assemblies. Refer to the wheel processor block diagram in Fig. 3. These units represent the custom hardware and firmware that were designed to build the AVDAC. The main functional blocks of the wheel processor are the switch event (mount or dismount) monitoring circuits, the weight sensor monitoring circuit, sample clock circuit, micro controller for data acquisition and data tagging, first-in first-out (FIFO) buffer, status register, and command register. The control and algorithm processor can enable, disable, or reset the wheel processors and read the status registers and FIFO buffers. Once enabled, the wheel processors operate independently of the control processor and monitor each wheel that passes over the sensor assembly via the switches. The data in the FIFO buffers are stored in chronological order and tagged for identification as switch events S1, S2, S3, S4 or weight data samples. The end of each wheel is also identified in the FIFO data stream. Wheels are timed and sensed until the control processor disables the wheel processors. Since the FIFO buffers have finite length, the control processor must actively remove data from them when the wheel processors are enabled. If the control processor should get behind, an error flag is set in the wheel processor status register, subsequently causing the program to signal the operator and abort the run. The most likely cause of a FIFO overflow is attempting to operate the system at very low vehicle speeds. After the control processor receives the end-of-vehicle signal, the wheel processors are disabled and the data are analyzed. Obvious noise points in the weight data samples are eliminated and a check is made for inconsistencies such as different number of axles on each side. If the data are found to have unacceptable errors, the operator is signaled to repeat the run. Otherwise, the vehicle parameters are calculated and the data displayed.

A flow diagram describing the operation of the wheel processor is contained in Figs. 4a, 4b, and 4c. Two timers, the axle timer and the pad timer, are used for wheel data acquisition. The axle timer runs at a slower rate than the pad timer and keeps track of the time between axles. The pad timer measures the time between individual switch events, subsequently enabling the calculation of tire velocity. The pad timer also establishes the sample rate for the weight readings. The AVDAC as tested used a pad timer with 250μs resolution and an axle timer with 10ms resolution. The

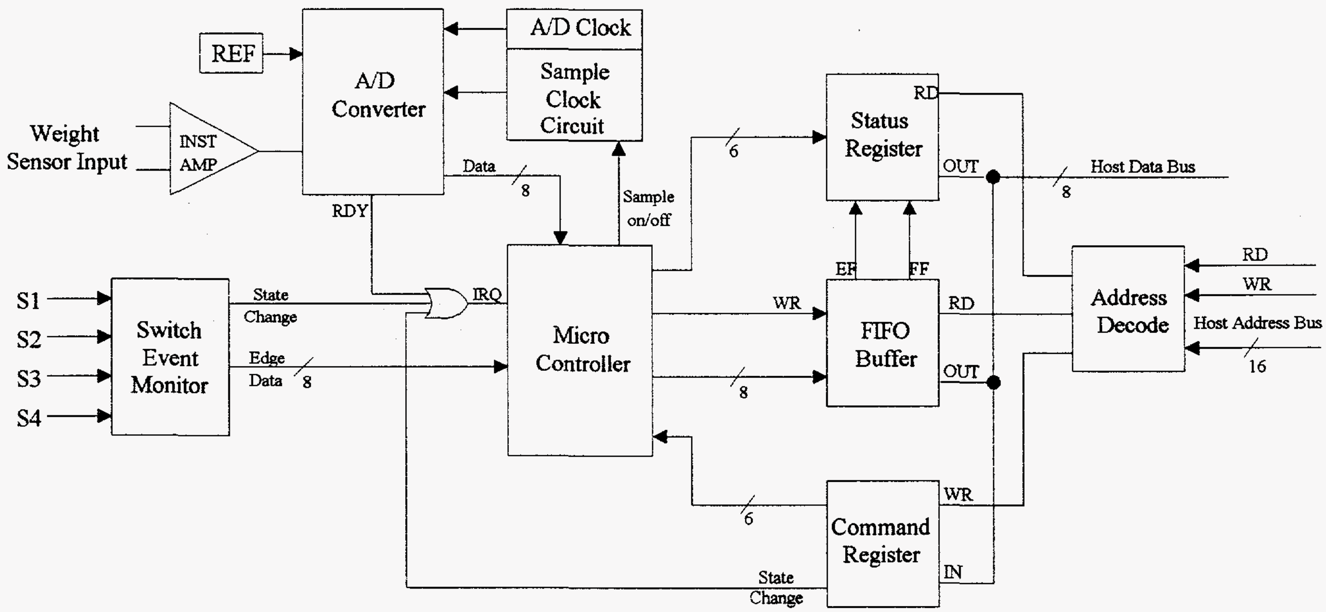

Fig. 3. Wheel Processor Block Diagram

beginning of each wheel is identified by the S1 switch mount event. In cases where the S1 switch fails to function, the S2 mount marks the beginning of the wheel. The first of S1 or S2 to be mounted at the beginning of each wheel is time stamped with the axle timer. At the beginning of each vehicle the axle timer is cleared, and the first switch to mount in the first wheel will have the time stamp of zero (t0). The first switch mount in each successive wheel is time tagged with the increasing axle timer value. All other switch events are time stamped with the pad timer. The first switch mounted in each wheel is always the t0 reference for the pad timer. When the weight sample clock is turned on, a maximum wheel watchdog timer is started. This watchdog will terminate data acquisition if the situation arises where neither S3 or S4 operates. Under normal conditions the dismount of the S4 switch signals the end of the wheel, and a special data signal is stored to the FIFO to clearly mark the end of wheel. To guard against situations where the S4 switch fails to operate, the dismount event of the S3 switch starts an end of wheel watchdog timer based on the current wheel pad mount time. This allows weight data acquisition to continue until just after the position where the S4 dismount would normally stop acquisition. The wheel acquisition could be achieved by simply starting acquisition on the first switch mount and stopping it on the first dismount of S3 or S4. The accuracy of the system is significantly improved by using all the switch timings for wheel velocity calculation and measuring the weight for the entire period of tire contact with the pad.

2.3 Bus standard choice

The STD bus standard was chosen for the hardware platform because, in addition to providing a rugged hardware

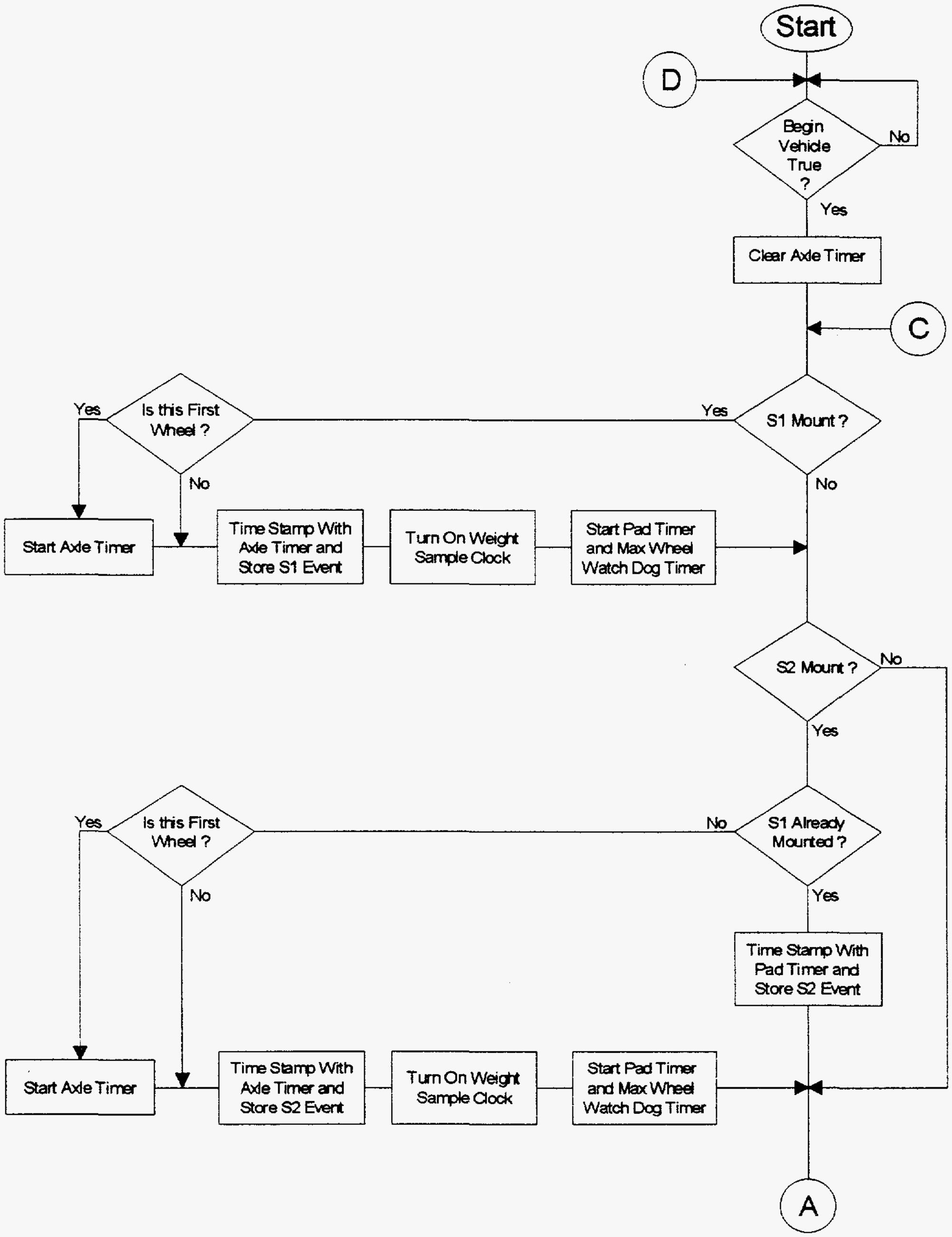

Fig. 4a. Wheel Processor Flow Diagram

environment, it also supports PC-based software development. The system allows mechanical disk drivers and a standard keyboard to be installed, implementing a software development environment that appears like a normal PC to the programmer. Once software development is complete, the keyboard and mechanical drives are easily removed without affecting the operation of the system. After software development is complete, the application software is loaded onto the solid state disk drive, and the autoexec.bat file on that drive is edited to run the application at power up. The mechanical drives and keyboard are removed, and the configuration setting is modified accordingly. This stripping away of the PC peripheral devices and development tools allows the PC to operate as an embedded computer. The hardware design is not limited to the STD platform and can be easily migrated to other configurations such as the Industry Standard (ISA) bus used in most PCs.

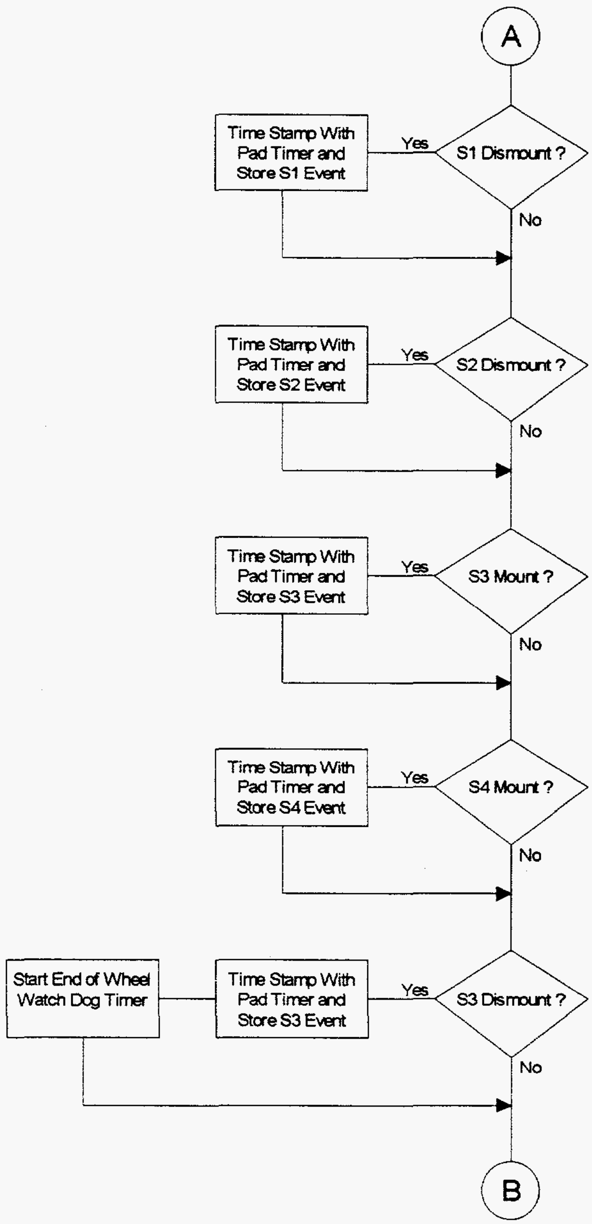

Fig. 4b. Wheel Processor Flow Diagram

2.4 System operation

To operate the system, the sensor pads and ramps are positioned on a hard, level surface such as a runway. The pads are spaced to accommodate the majority of vehicle wheel path widths that will be weighed. On occasion, it may be necessary to reposition one pad to weigh a vehicle that has an unusually narrow or wide wheel path. The electronic monitoring system is located in a convenient position away from the path of vehicles. Once the system is set up and vehicles are ready to proceed, the operator arms the system and signals the vehicle to approach. The system can be armed anytime before the vehicle mounts the ramp system. Each time the system receives the "begin new vehicle command," the system performs an analog to digital (A/D) converter calibration check and tests the sensor pads for any change in the unloaded weight. The A/D converter used is a self-calibrating type that adjusts for any zero, full-scale, or linearity errors. The operator visually monitors when all the axles of the vehicle being weighed have exited the ramps and then sends the "end of vehicle command" with the key pad. When the system receives this signal, it calculates the vehicle parameters and displays them. If everything seems normal, the operator prints out the vehicle data and signals the next vehicle to approach.

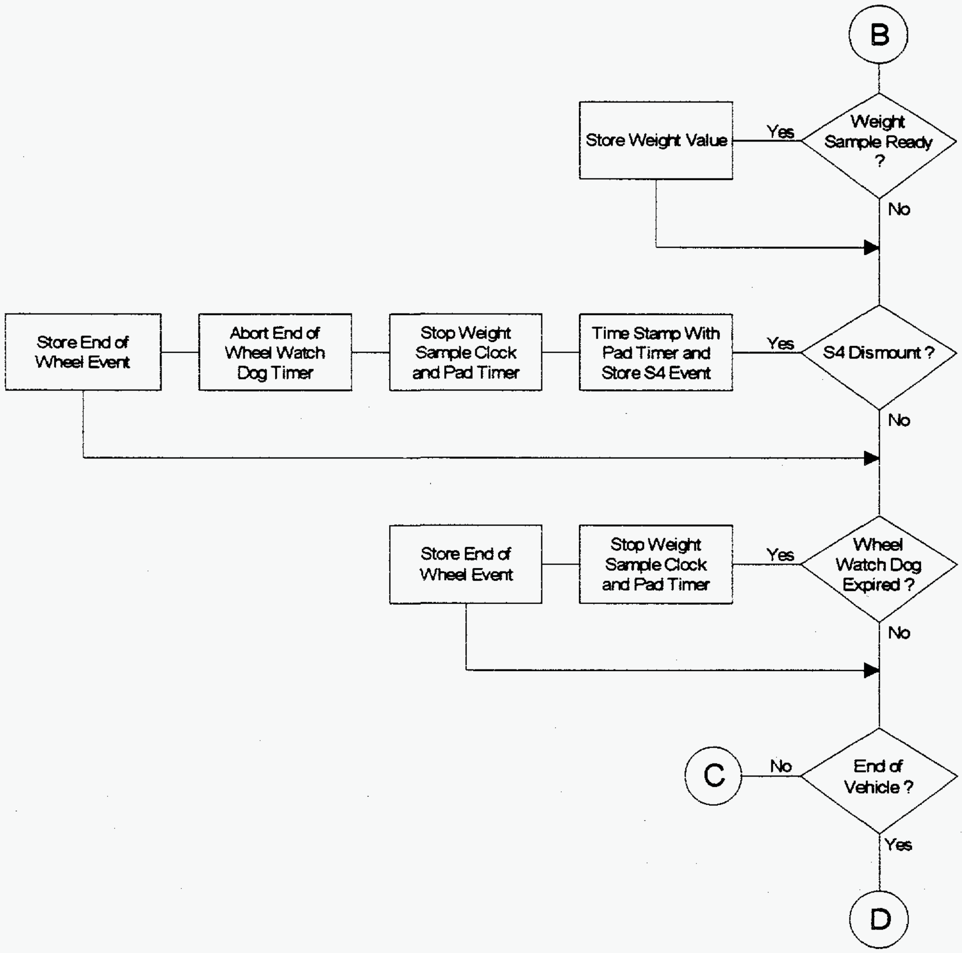

Fig. 4c. Wheel Processor Flow Diagram

PRINCIPLES OF OPERATION

Dynamic weighing sensors rely on an "ideal" response of a vehicle's tires rolling over a linear sensor. Examination of the data from many hundreds of vehicle test runs on a smooth and level roadbed indicate that the "ideal" response is achieved less than 75% of the time. Less favorable road conditions will exacerbate this situation. Observed tire response waveforms sometimes exhibit two or more peaks as a result of suspension dynamics. Additionally, if a tire's footprint is longer than the active area of the weight sensor, not all of the tire's weight will be included in the peak. To compensate for tire responses that are less than ideal and also accurately measure tires that distribute weight over an area wider than the sensor, a weight-by-integration method is used. To perform the weight-by-integration method, it is essential that accurate tire velocity measurements be obtained. Accurate center-of-balance calculations also require good velocity measurements because the axle separation measurements rely on knowing the vehicle speed.

3.1 Velocity determination

As shown in Fig. 1, the distances between the pad switches S1, S2, S3, and S4 are known. After the frontal edge of a tire contacts the first switch, the time elapsed for that edge to contact each successive switch is measured with a 4000-Hz clock. At 1 mph the surface of a tire travels at 17.6 inches per second and at 5 mph at 88 inches per second. The tire velocity is calculated by the following formulas:

$$v_a = \frac{d_{S3-S1}}{t_{S3-S1}} \qquad v_b = \frac{d_{S4-S1}}{t_{S4-S1}} \qquad v_c = \frac{d_{S3-S2}}{t_{S3-S2}} \qquad v_d = \frac{d_{S4-S2}}{t_{S4-S2}}$$

v_a, v_b, v_c, v_d = Tire Velocity $d_{S3-S1}, d_{S4-S1}, d_{S3-S2}, d_{S4-S2},$ = distance between switches

$t_{S3-S1}, t_{S4-S1}, t_{S3-S2}, t_{S4-S2}$ = time between switches

If all four velocities are available, then the high and low values are thrown out, and the remaining two are averaged together to arrive at the tire velocity. If only three velocities are available, then the high and low values are thrown out, and the remaining one is used as the tire velocity. If two are available, then they are averaged for the final velocity; and if only one is available, then it becomes the velocity. All the individual tire velocities of the vehicle are accumulated and averaged together to obtain the vehicle velocity. This velocity in inches per second is divided by 17.6 to arrive at the vehicle speed in miles per hour.

3.2 Axle spacing determination

The first axle of a vehicle is always time zero and is the reference to measure the other axles of the same vehicle. A 100Hz clock is used to measure the elapsed time of occurrence of each successive axle from the first. This time is based on the first detection of the tire frontal edge. Allowances are made for cases when the axles are detected by different switches, (i.e., one by S1 and the other by S2). The axle spacing is calculated by multiplying the average of the two adjacent tire velocities by the time between the axles. Tires contact the roadway with a surface area that can vary in length in the direction of travel from tire to tire. This variation is caused by different tire inflation, load, and type and averages anywhere from 2 inches to 20 inches. On large load-carrying vehicles, the difference in length of tire footprint from one axle to the next can be significant. To compensate for this, the axle switch "mount time" and the tire velocity are used to calculate the tire footprint length. The "mount time" is the event time of the switch mount subtracted from the event time of the dismount and reflects how long the tire was on the switch. The lengths are calculated using the following formulas:

$$L_{S1} = S1_{mt} * v_{tire} \qquad L_{S2} = S2_{mt} * v_{tire} \qquad L_{S3} = S3_{mt} * v_{tire} \qquad L_{S4} = S4_{mt} * v_{tire}$$

$L_{S1}, L_{S2}, L_{S3}, L_{S4}$ = Tire length calculation V_{tire} = Tire velocity

$S1_{mt}$ = Switch 1 mount time $S2_{mt}$ = Switch 2 mount time $S3_{mt}$ = Switch 3 mount time $S4_{mt}$ = Switch 4 mount time

The same averaging scheme used to arrive at a final tire velocity in Section 3.1 is used to arrive at a final tire length value. To obtain the adjusted distance between two adjacent axles, one-half of the leading axle tire length is subtracted from the axle spacing measured between tire frontal edges, and on-half of the trailing axle tire length is added to that distance. Refer to Fig. 5 for a pictorial explanation of adjusted axle spacing determination. The values obtained from this method for the left and right side of the vehicle are averaged together to arrive at a final axle spacing distance.

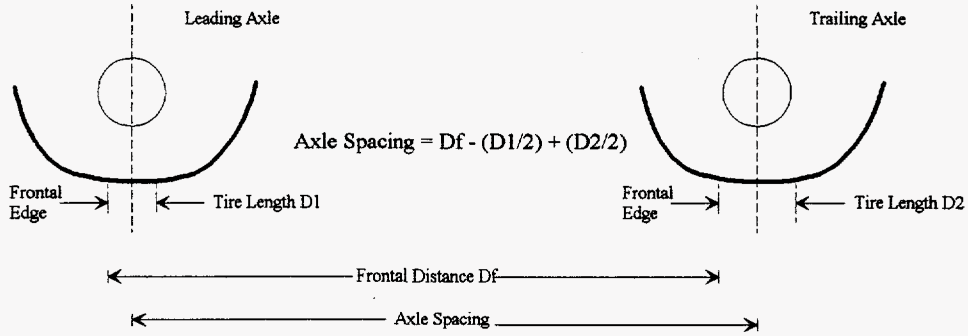

Fig. 5. Axle Spacing Determination

3.3 Tire and vehicle weight determination

The weight sensor sample points collected for each wheel are adjusted for no load offset and summed together. To arrive at the tire weight this sum is multiplied by the tire velocity and a calibration constant. The following formula represents how tire weight is calculated:

$$w_t = \sum_{1}^{n} \left(w_p - w_{offset} \right) * v_{tire} * k_{calibration}$$

w_t = tire weight w_p = weight of one point w_{offset} = no load weight reading v_{tire} = tire velocity

$k_{calibration}$ = calibration constant n = number of samples

Individual axle weights are determined by adding the tire weights on each side of the axle together. The total vehicle weight is obtained by adding all the tire weights together.

3.4 Center-of-balance determination

To find the center of balance, the product of each axle's weight and distance from the first axle is divided by the total weight. Since the first axle is the reference, the distance for that axle will always be zero. The following formula is used for the center-of-balance calculation:

$$CB = \frac{d_1 w_1 + d_2 w_2 \cdot\cdot + d_n w_n}{w_1 + w_2 \cdot\cdot w_n}$$

d = distance from first axle n = total number of axles w = axle weight

4. CONCLUSIONS

This project demonstrated that a portable weigh-in-motion system can automate the manual procedure currently used by the military to manifest vehicles for air transport. Weight and center-of-balance measurements with an accuracy range of ±3.0% to ±6.0% can be made on vehicles moving from 1 to 5 mph. In dynamic weighing systems, the weight by integration method will improve system accuracy by reducing the effect of suspension motion on measurements.

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6. REFERENCES

1. J. H. Wyman, "An Evaluation of Currently Available WIM Systems," pp. 6-13 in 3rd National Conference on WIM Proceedings, St. Paul, Minnesota, October 1988.

2. B. Izadmehr and C. E. Lee, "On-Site Calibration of WIM Systems" Transportation Research Record 1123, Transportation Research Board, National Research Council, Washington, D.C., pp. 136-144, 1987.

3. P. Davies and F. Sommerville, "Calibration and Accuracy Testing of WIM Systems, "Transportation Research Record 1123, Transportation Research Board, National Research Council, Washington, D.C., pp. 122-126, 1987.

4. C. E. Lee, "Factors That Affect the Accuracy of WIM Systems," pp. 14-23 in 3rd National Conference on WIM Proceedings, St. Paul, Minnesota, October 1988.

5. W. D. Cunagin, "WIM System Accuracy, " pp. 24-29 in 3rd National Conference on WIM Proceedings, St. Paul, Minnesota., October 1988.

6. J. D. Muhs et al., "Results of a Portable Fiber-Optic Weigh-in-Motion System," pp. 374-386 in Proceedings of the International Society for Optical Engineering, Vol. 1584, September 1991.

7. J. R. Rickaway, personal communication, "Summary of Tests of the Automated Vehicle Data Acquisition System," April 20, 1995.