Texas A&M
Transportation
Institute

Draft Specification for Compaction Monitoring System

Product 0-6874-P3

Cooperative Research Program

DRAFT SPECIFICATION FOR COMPACTION MONITORING SYSTEM

by

Bill Crockford, PhD, P.E.
Research Engineer
Texas A&M Transportation Institute

Wenting Liu, PhD, P.E.
Associate Research Engineer
Texas A&M Transportation Institute

and

Younho Rew, PhD
Postdoctoral Research Assistant
Texas A&M Transportation Institute

TEXAS A&M TRANSPORTATION INSTITUTE
College Station, Texas 77843-3135

DISCLAIMER

ACKNOWLEDGMENTS

Special Specification XXXX
Compaction Monitoring System (Method)

1.   **SCOPE**

Use this method to obtain a real-time and post-construction assessment of breakdown roller compaction effectiveness. This method includes procedures for determining compaction index (CI) using a compaction monitoring system (CMS). This method is not to be used for pay factor or acceptance decisions.

2.   **APPARATUS**

2.1.   **Compaction Monitoring System.**

2.1.1.   The CMS is comprised of:
- a data acquisition system with removable data storage (e.g., SD card, USB drive),
- a screen for user input and data presentation,
- stand-alone power (e.g., battery) or ability to interface with the compactor's electrical system,
- global positioning system (GPS) with differential capability (e.g., WAAS or RTK),
- accelerometer(s), and
- thermal sensor(s).

2.1.2.   As a minimum, the CMS shall store data from all sensors and a computer-generated time stamp. The CMS may use any available GPS sentence structure.

Note 1—During development of the CMS, NMEA 0183 RMC version 2.30 active and WAAS enabled was used with Garmin equipment, and GGA and others were used with Trimble equipment. A data acquisition/output rate of 1 Hz was found to be acceptable. Single-axis and multiple-axis accelerometers were used in development of the CMS. It is recommended that a multiple-axis accelerometer be used if the compactor model incorporates an oscillatory or tangential vibration feature.

2.1.3.   The CMS shall be capable of operating for at least one full construction day in typical asphalt construction environmental conditions without recharging the battery.

3.   **PROCEDURE**

3.1.   Install the compaction monitoring system in accordance with the manufacturer's recommendations. See the Appendix.
- Ensure sensors and CMS package are securely mounted to the roller, will adequately sense the desired parameter (e.g., GPS antenna reception is not blocked by structural parts of the compactor), and will not interfere with moving parts of the compaction equipment.
- Instruct operators that compactor operation is the first priority and they should only use the CMS display as an additional part of their instrument scan.

Note 1—Location identification is done solely by GPS.
Note 2—Contributions to the CI are only counted while the paver is moving (i.e., passes are not counted in the measurement if the compactor is not moving or is moving slower than a threshold

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value; generally a threshold within the ground speed noise level of the GPS may be used to control this).

3.2.   Verify the calibration for each temperature sensor prior to collecting temperature measurements per manufacturer's recommendations.

Note 3—Check calibration of each temperature sensor to a known standard on an annual basis and recalibrate if necessary. Document the yearly check/calibration result.

3.3.   Initiate data collection with the CMS following the manufacturer's instructions to automatically generate and store information from the CMS. Data file storage shall be robust in the sense that unexpected issues such as a power failure do not result in corruption or loss of the data file. As a minimum, the data file must include, in a *.CSV format:

- Date/time stamp, preferably to 0.1 s precision.
- Latitude.
- Longitude.
- Speed.
- Temperature(s).
- Acceleration(s).

Additional information is recommended, for example, the full GPS sentence and user input such as identifying comments/remarks.

4.   CI CALCULATIONS

4.1.   The CI is a summation of the effects of roller passages over a given point. Each coverage over the point is weighted by at least three factors: drum position, mat temperature, and vibration. For the purposes of the CMS, a "pass" is one "coverage" of a point, so a trip by the roller up to the laydown machine and back to the starting point is construed as two passes. Operators should be aware of this interpretation of the meaning of the word "pass" because it is not interpreted the same by all paving crews.

4.2.   The real-time and/or post-processor shall perform the following calculations for reporting purposes:

$$CI = CI + \left(\left(\frac{Drum\ Factor}{Effective\ Compaction\ Effort} \right) * Temperature\ Factor * Vibration\ Factor * 100 \right)$$

where the effective compaction effort is related to the planned rolling pattern, and the drum, temperature, and vibration factors are computed as described in Research Report 0-6874-2.

APPENDIX: CMS OPERATOR'S MANUAL

OVERVIEW

The compaction monitoring system (CMS) records global positioning system (GPS) position, mat temperature, and machine compaction drum acceleration for breakdown rollers on hot mix asphalt. The CMS uses this information to provide input to roller operators for adjustment of the compaction process. The operator is not required to use the data in real time since the system may be set up and allowed to run unattended during the compaction operation. Post-processing of the acquired data can be used for forensics and quality measures. Figure 1 shows the CMS system in a programmable logic controller (PLC) form factor.

Figure 1. CMS.

HARDWARE OPERATION

Case Unpacking, Connections, and Sensor Mounting

Two Pelican cases are used to transport the system. The larger case contains the PLC and human-machine interface (HMI). The smaller case contains the instrumentation sensors, wiring, Velcro strips, and mounting magnet systems for the GPS antenna, infrared temperature sensor, and accelerometer. Two types of magnets are used for mounting to the compactor: a standard magnet and a switched magnet. The switched magnet is a mechanical device that attaches and detaches by alignment of magnetic fields using a knob. Rotating the knob clockwise about 180 degrees to where the knob stops will attach the magnet. Rotating counterclockwise will release

the magnet. The Velcro strips are available for attaching the wiring and main PLC instrument case to the compactor.

In general, the user should mount the accelerometer on the vibrating drum if possible. If it is not possible to mount the accelerometer on the vibrating drum, the user should mount the accelerometer in any convenient location to try to pick up the vibration of the roller. Figure 2 shows the accelerometer and temperature sensor.

NOTE: The accelerometer is a three-axis accelerometer. The mounting system allows the user to place any of the three axes in the vertical direction, but it is preferred that the Z-axis be up, which is perpendicular to the square face of the sensor (as in Figure 2).
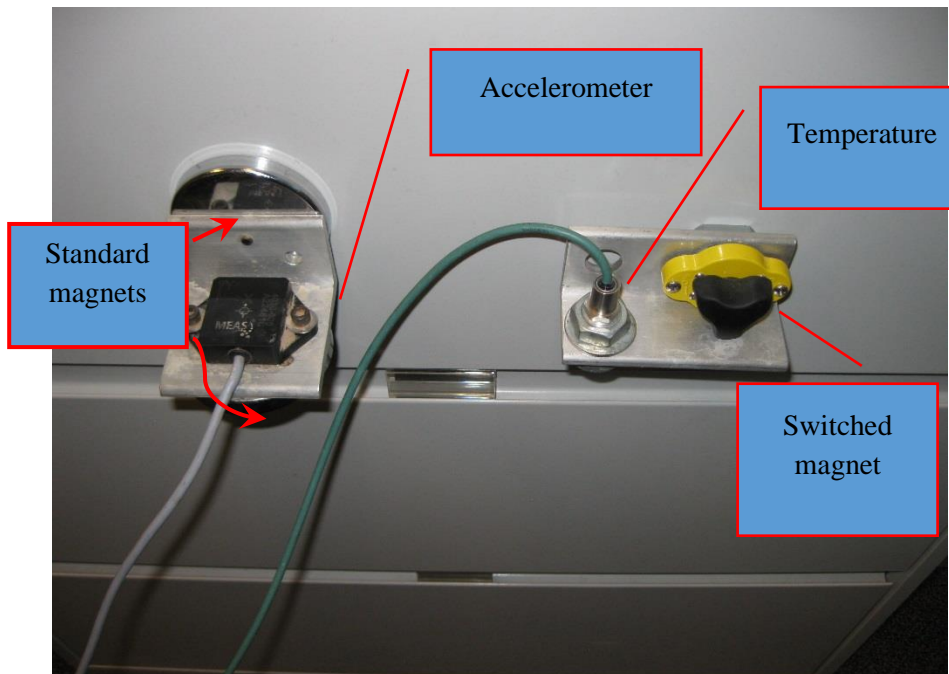
Figure 2. Accelerometer and Temperature Sensor (mounted on front of filing cabinet drawer for illustration).

The temperature sensor should be installed pointing downward and reasonably close to the surface of the pavement. Normally, the user should place this sensor on the back of the operator structure below the articulation joint at the lower edge of the casting and near the middle of the width of the compactor.

The GPS antenna is mounted on a cantilevered arm (Figure 3); it has a screw that attaches from below, and the head is not fully recessed. Generally, the user should allow the bolt to overhang the cab so that the full strength of the magnet is applied to the roof when mounting the GPS on the roof/roll over protection structure of the compaction roller.

Figure 3. GPS Antenna Mounting.

Connections

The PLC case has connector receptacles on one end, as shown in Figure 4. The BNC connector is for a Trimble GPS antenna that is no longer used. The user should use the upper left connector for the current Garmin 19x HVS GPS system by pushing to connect and pulling on the outer housing to disconnect. The large connector with the cover on it connects to an HMI and is not currently used since the HMI is now mounted in the case.

The user should connect the accelerometer to the 6-pin connector and the temperature sensor to the 4-pin connector. For these two connectors, line up the indexing detent on the cable end with the receptacle detent on the case and push the cable onto the receptacle. Then turn the outer ring on the cable end about 1/4 turn to lock it in place. Do not overtighten because doing so will rotate the receptacle in the side of the case. To avoid overtightening, it is recommended that the cables be installed while the case is open, and the back side of the connectors can be monitored for unwanted movement. Reverse the process to remove the cables.

Figure 4. Connectors on CMS Case End.

PLC Case Components and Operation

Figure 5 shows the inside of the CMS case. The main system on/off switch is inside the case. This switch powers all the devices (sensors, GPS, HMI, etc.). The PLC also has a run/term/stop switch on it. The PLC must be in the RUN position to take data. Either of the other two positions will result in no data being acquired. There is an indicator on the HMI that will show a change to the RUN position from either of the other two positions.
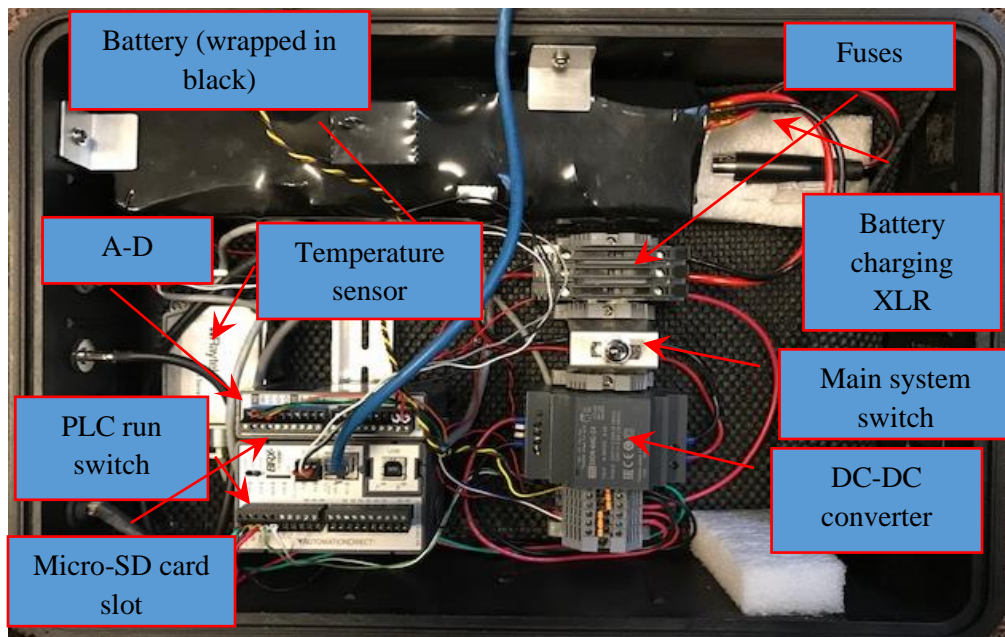
Figure 5. Inside of CMS Case.

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The recommended order of operation is as follows:

- With PLC switch and main power switch in the STOP/OFF position, turn the main power on and leave the PLC switch in the STOP position for a short time while the GPS and HMI systems come online. It normally takes about 1–3 minutes for the HMI to boot up and the GPS to acquire a signal.
- Move the PLC switch all the way to the RUN position. At this point, the system is running/taking data and the HMI display should confirm that on the main screen.
- After test completion, move the PLC switch to the STOP position, and then turn the main power switch off before removing the SD/micro-SD cards to back up the data on a computer.

The HMI has no on/off switch, so it will turn on when the main system on/off switch is turned on. If the HMI fails but the battery is still good, the PLC is running, and the PLC micro-SD card has room for data, the system will still acquire data for as long as it is left on, and the data on the micro-SD card can then be analyzed using the PC post-processor after the test.

NOTE: The HMI is also equipped with a slot for an SD card (does not require a micro-SD; Figure 6). In the latest version of the CMS, this SD card is used to store both the HMI program and screen captures of the HMI display. The following screen captures are performed:

- The setup screen and the home screen are captured each time the setup screen is closed.
- The main (home) screen is captured every 10 minutes.
- The history screen is captured every 30 minutes.

The power supply is a nominal 24VDC battery. When fully charged, it will show about 29.4VDC on a voltmeter. When voltage drops to about 18VDC, the system may shut down and the battery should be recharged. The battery has a dedicated wall charger with a special (XLR) connector on it, and only this charger should be used to recharge the battery. A full day or more of operation is possible on one charge. The PLC, analog to digital board, GPS, and sensors are driven by 24VDC, which is provided by a DC-DC converter that maintains 24VDC output regardless of the battery voltage level between 18 and 29.4VDC.

While the PLC can store data in its on-board memory, a micro-SD card (32 GB maximum capacity) is used to store the CMS data. Figure 6 shows where this card is inserted and removed from the PLC by a spring-loaded catch. The catch works like a push button: to install, put the card in and push until it latches; to remove, push the card in again and release, and it will pop up for removal. Make sure the micro-SD card electrical contacts are facing the right way before inserting it; forcing it may break the tabs or locking mechanism.
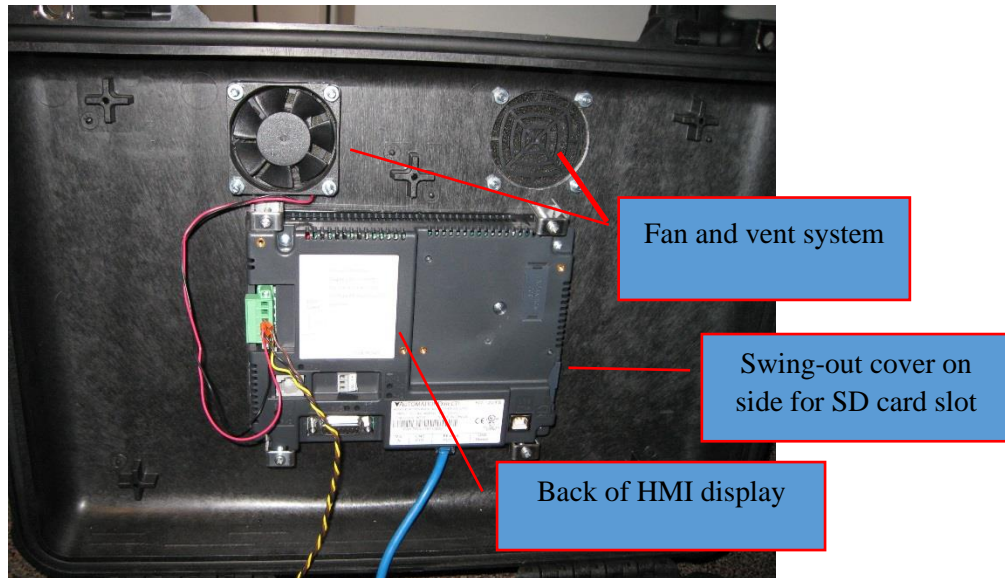
Figure 6. Inside View of PLC Case Lid.

There are small LEDs on the front of the PLC that indicate the status of various functions such as the micro-SD card (LED is green when the card is inserted/detected) and communication ports (RS232/485 and Ethernet port LEDs are green when working). Generally, these LEDs will be green and/or flashing during normal operations. Because the PLC writes data as it goes, there is no issue with a file being open when power is removed. The file should close without error and the data should be intact. However, moving the PLC switch to the STOP position before the main power switch is turned off is the preferred shut-down approach. Figure 7 shows the meaning of the LED indicators on the PLC.

CPU Status Indicators		
Indicator	**Status**	**Description**
PWR	OFF	Base Power OFF
	Green	Base Power ON
	Yellow	Low Battery
RUN	OFF	CPU is in STOP Mode
	Green	CPU is in RUN Mode
	Yellow	Forces are Active
MEM	OFF	No ROM Activity, No SD Card
	Yellow	ROM Activity (Flash or SD Card)
	Green	SD Card Installed and Mounted
	Red	SD Card Installed and Not Mounted
ERR	OFF	CPU is functioning normally
	Red	CPU Fatal Hardware Error or Software Watchdog Error

Figure 7. PLC LED Indicators.

In general, it has been found that placing the PLC case on what normally is the operator's right side is the preferred location so that it is out of the way of most of the operator's seat movement. During R&D and when the operator is not actively using the display, the HMI display is normally positioned so that it can be seen from the side. Usually, the PLC case is merely attached to the railing structure on the compactor using at least two Velcro straps or bungee cords so that the case stays upright.

HMI OPERATION

Home Screen

When the system is turned on, the HMI will open on the home screen. Figure 8 shows the screen, followed by a description of the features.
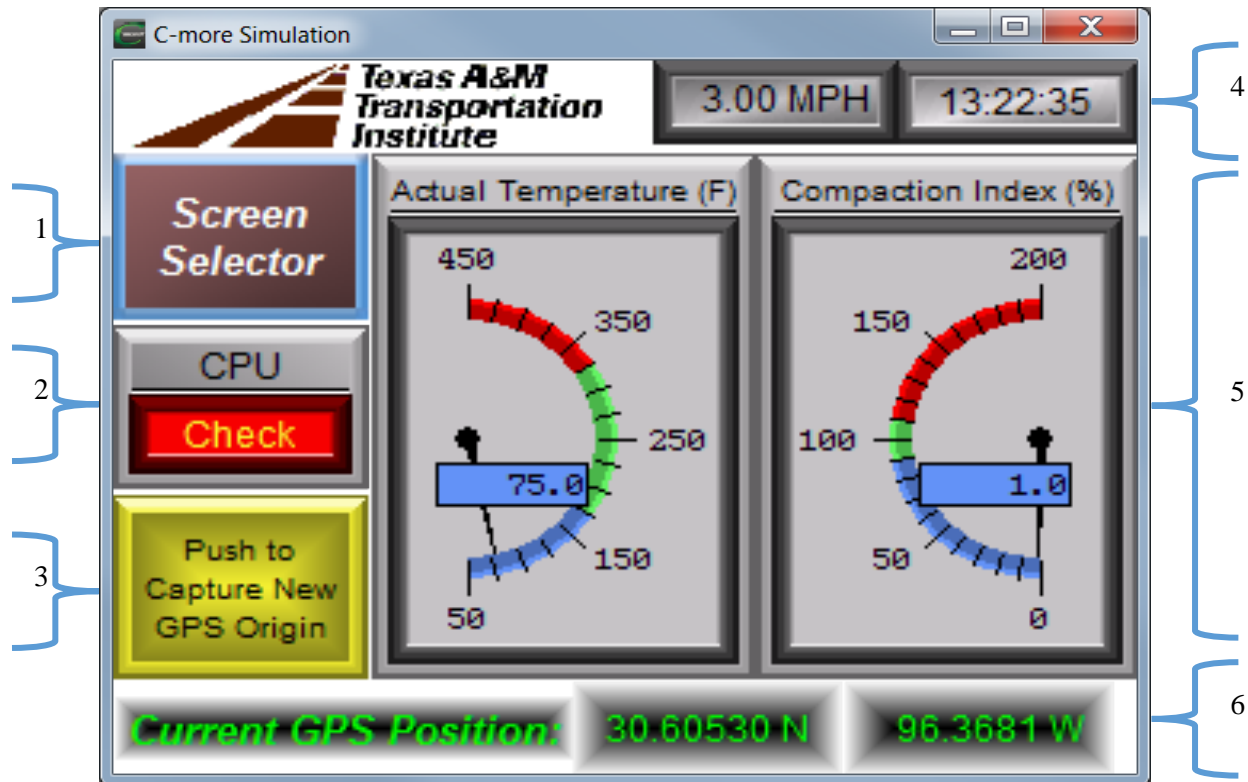

Figure 8. HMI Main Screen.

1. The screen selector button is used to go back and forth between the home screen, the history plot screen, and the job setup screen. The CMS will continue to run, regardless of which screen is showing on the display.
2. This indicator will flash "Check" with a red background when the PLC switch is not in the RUN position. It will show "Running" in green when the switch is in the correct RUN position. The system will not collect data if this indicator is flashing red.
3. There is a column in the data output file that stays at a value of zero if this New Origin button is never pressed. If the button is pressed, it will change the value from 0 to 1 and will remain 1 until the button is pressed again, at which time it will change back to 0. This button can be pressed as many times as desired during the job, and it will toggle the value back and forth between 0 and 1. However, it is normally used to indicate where different treatments occur during the experiment (e.g., switch from a dense-graded mix to an open-graded mix). The value (0 or 1) will be output as a part of every record observation (i.e., after pushing the button, the value will be written as part of every observation until it is pushed again to take on the new value). Each time the button is pressed, it also resets the storage locations for the compaction index (CI) display.

4. The clock time of day and the GPS ground speed are shown in this area. At very low speeds, the GPS speed may not be very reliable.
5. The two main displays are shown in the middle of the HMI.
    a. The temperature display shows the current temperature (°F) with the needle and the digital display. The range of the color-coded bands of the arc in the display can be controlled by the user in the job setup screen, but the end point values (50 and 450 in this case) are fixed.
    b. The compaction index shows the calculated index. The target is generally 100 percent, but the range of the color-coded bands of the arc in the display can be controlled by the user in the job setup screen, and again the end point values (0 and 200 in this case) are fixed. When the power is switched on and the PLC is running, the pointer will point at 1, just off the minimum value in the arc, so that the user knows it is operating. However, it will not update above that value until sufficient data have been taken. The update rate for the pointer is slower than the data rate used to store data on the micro-SD card, primarily because of limitations in PLC memory capacity relative to the unknown total length of the job. Even though the PLC is scanning very fast (averaging approximately 1.25 kHz for this program), the non-volatile raw data storage rate to the micro-SD is 1 Hz due to GPS settings and file size considerations. The volatile CI real-time display is performed at a slower rate of once every 15 seconds for 20 minutes, at which time it automatically resets and starts displaying new values. If the automatic reset occurs, for example, in the middle of a pass, the CI display may not be accurate for a short period after the reset. When the automatic reset happens at 20 minutes, the weighted accumulated CI measurements that have been displayed in that 20-minute block have been deleted, and review of the older data can only be performed by using the post-processor with the raw data as input.
6. The current location in degrees is displayed here. This value is not as precise (i.e., not displayed to as many digits) as the coordinates being written to the micro-SD card.

Data History Screen

Figure 9 shows the time history screen. The amplitude (Y) scale is sized to accommodate the acceleration value from the Z-axis of the accelerometer in g and the GPS speed in mph. However, the scale does not show negative values of the Z direction acceleration, nor does it show values more than 5 g even though the sensor will read up to 6 g. Because the temperature will be large compared to the other two variables, the temperature plotted on this graph has been divided by 100 to fit within the 0–5 scale. A description of this screen is listed below the figure.
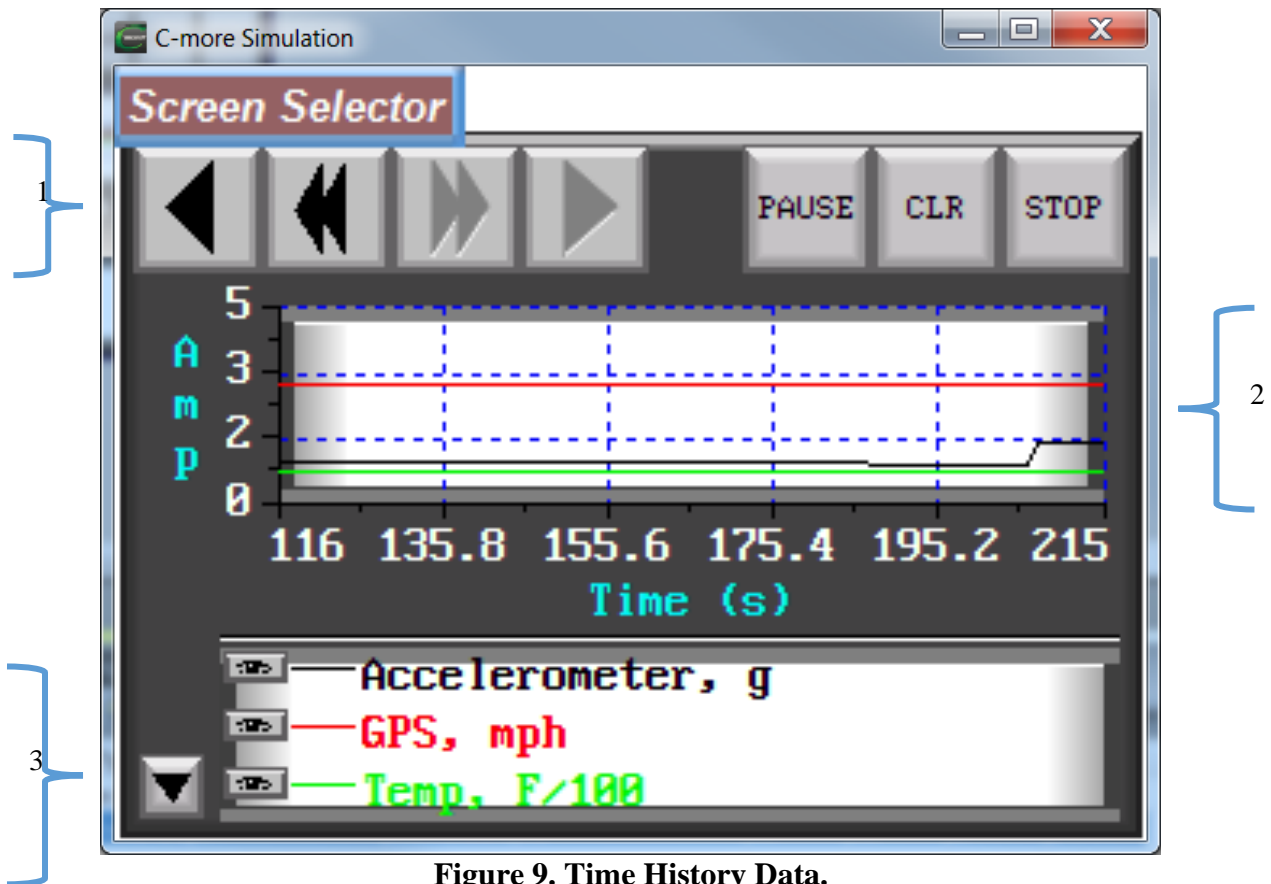
Figure 9. Time History Data.

1. Control buttons. These buttons can be used to pause, clear, or stop the plot, and to play forward or backward in time. The double arrows can be used to jump to the start of the plot or end of the plot.
2. Plot area.
3. Legend area. By using the small down arrow at the bottom left of this area, the legend can be hidden, which simultaneously increases the size of the plot area. To the left of each legend (e.g., GPS, mph), there is a small box just at the left end of the color-coded line. Clicking this box causes the plot line for that variable to be dropped from the history plot. The box works like a toggle, so any variable can be turned off or on as desired. Because of the screen size limitation, only three variables are included for plotting in order to minimize clutter on the plot, but more and/or different variables are possible.

Job Setup Screen

Figure 10 shows the job setup screen, which is generally used for only two purposes: (a) to enter data at the start of the job related to parameters that will usually remain static throughout the job (e.g., drum width of the roller), and (b) to identify locations of test points (e.g., cores) at the end of the job. However, the user may change any value on this screen at any time, and it will take effect when it is entered. A description of the job setup screen inputs is listed below the figure.
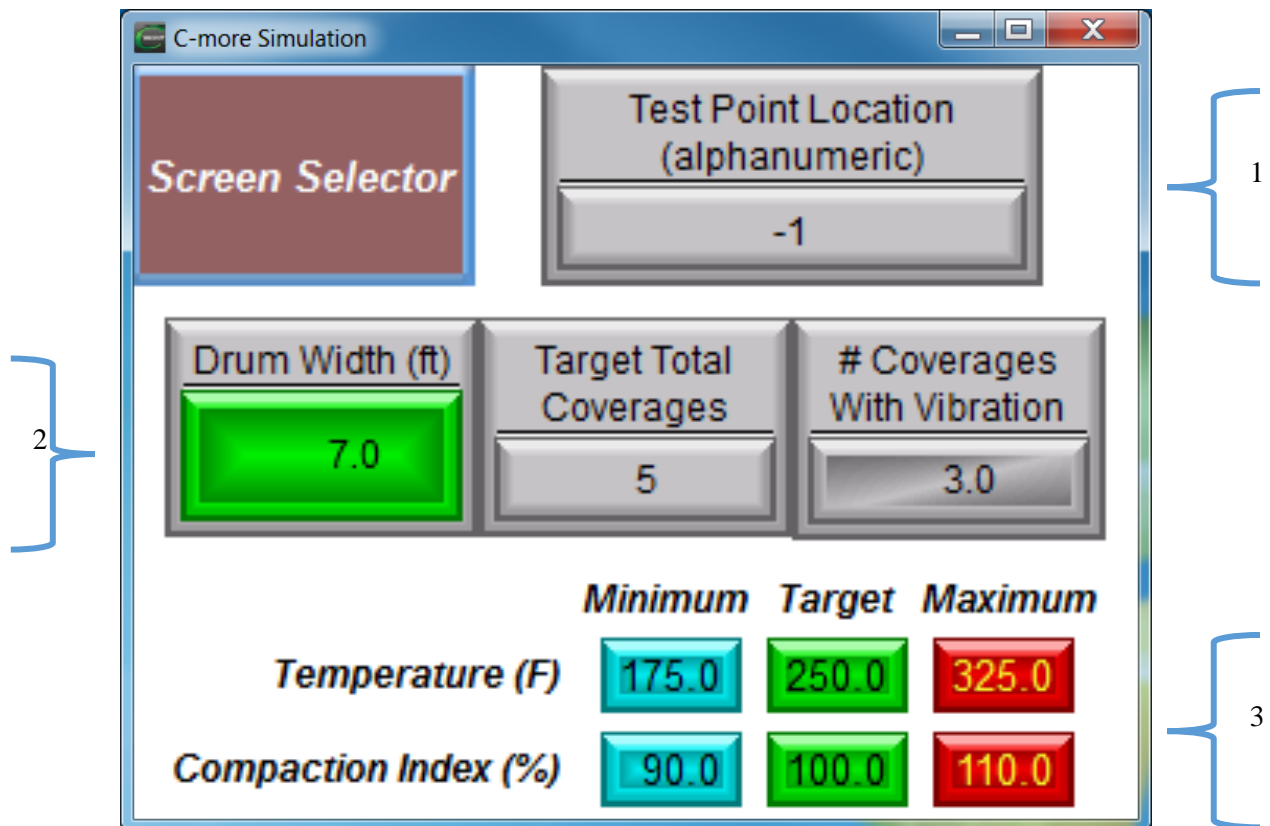
Figure 10. Job Setup Screen.

1. The Test Point Location text entry button allows the user to put a comment in each record of the data file. This is intended for short comments (e.g., for a core identification with a number and letter, as in 15A), but longer comments are possible. In the data file, this is a separate column from the New Origin 0 to 1 toggle value that is discussed in the home screen, and it operates differently. The default value of the comment is −1. When the button is pressed, a text entry form will pop up and the user can type in an alphanumeric string. This string will be written out with every observation until the user changes it again. A typical use for this is to identify core locations as follows:
    a. At the end of the job, leave the system running and remove the system from the compactor without disconnecting the sensors (at least the GPS) from the main PLC case if possible. If the system must be shut down and the sensors disconnected, that is not a problem, but the GPS will need to reacquire the satellites prior to taking the core locations. However, it is recommended that the core locations be measured as soon as possible after removing the device from the compactor so that minimum time passes for accumulation of position errors.
    b. Take the system back to the core location(s).
    c. Place the GPS antenna (and optionally the temperature and accelerometer, if desired) on top of the core location on the pavement.
    d. Press the Test Point Location button and enter the core ID, for example, 15A in this example (Figure 11).
    e. When pressing ENTER on the text entry screen, the text entered will be written out in every record in the data file until it is changed again.

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f. It is recommended that the user leave the antenna on the core location for about 30 seconds so that several data records will be written to the micro-SD card data file.
g. When ready to move to the next core, it is recommended that the user press the Test Point Location button again and reenter the default value of −1 before picking up the antenna so that there is a clear indication in the data file as to where the data for the core location starts and stops.
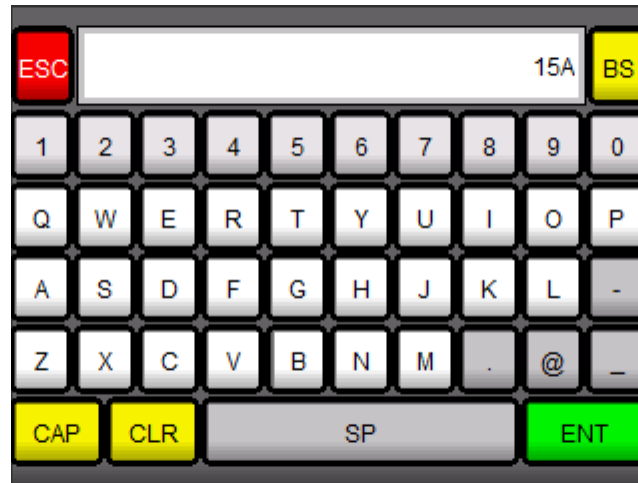
Figure 11. Test Point Location Text Entry Screen.

2. The drum width is specified in feet and converted to meters inside the CMS data processing. The total coverage means the total number of times that the operator's seat is intended to pass over any given point according to the rolling pattern. The number of coverages with vibration is not in addition to the total. Therefore, in this example, the rolling pattern is five total coverages, three of which should be using vibration and two of which should be static. The vibration coverages are not required to be integers at this time, so data entry may include a decimal value.

3. This area of the screen allows the user to control what the color-coded bands look like on the home screen.
    a. In this case, the part of the temperature arc that is between 175°F and 325°F will be color coded green. The target value does not necessarily need to be in the middle of this range.
    b. The part of the compaction index arc that is between 90 percent and 110 percent will be color coded green in this case. The target value does not necessarily need to be in the middle of this range.
    c. *NOTE:* All of the entries in this area of the screen are primarily there to customize the home screen display to the user's preferences with the exception of the target temperature. If the user has the temperature factor switch on the CI defaults screen in the ON position, the target temperature is also used by the temperature weighting factor equation to apply the appropriate weight to the computed CI.

Compaction Index Defaults Screen

Figure 12 illustrates the screen used to set up defaults that affect the compaction index calculations. It also displays the version (V2.3 in this case) being used in the PLC. The minimum speed data entry button allows the user to set a threshold value in knots for how fast the compactor must be moving before the CMS will start/continue computing the CI. Compactor movement slower than this value will not trigger CI computation, but the CMS will continue to collect raw data (e.g., position, temperature, acceleration, etc.) for the entire time even if the compactor is not moving. The user may select or deselect which weighting factors go into the calculation of the CI on the home screen meter display. The default positions of the switches are shown in the figure. If the user turns all of the switches off, the weighting for all three factors is assigned a value of 1.0, and since the weighting factors are only multiplicative in V2.3, the CI display will effectively count passes and show what percentage of the rolling pattern has been completed based on passes alone. However, even when all the weighting factors are turned off, the roller must still pass over the spot being measured in order to count as a pass (i.e., the spot does not register another pass if the edge of the roller passes more than ½ the drum width away from the spot on either side).
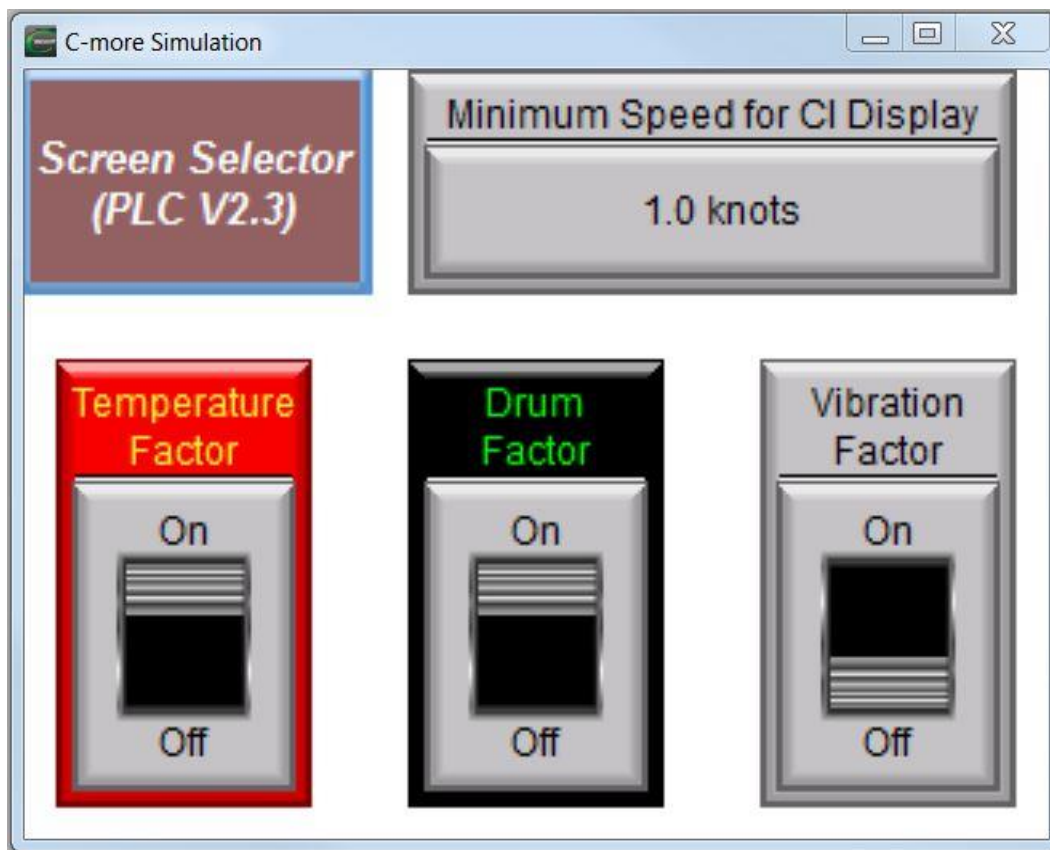

Figure 12. Defaults for Compaction Index.

Data File Format

The data file can be directly imported into Excel or other programs for post-processing. However, the recommended CMS post-processor has several features that would be difficult to

replicate in Excel. The data file name is automatically generated. The filename is in the format CMS_DoW_HHMMSS.csv, where DoW is a number corresponding to the day of the week (e.g., 3=Wednesday), and HHMMSS is the hour, minute, and second that the test was done. If the user stops and restarts the program, it will generate a new file unless it is restarted within 1 second, in which case it will append the new data to the existing data.

Table 1 documents the V2.3 output data file record format. Previous versions had fewer columns of data, and more columns than are shown in the table were used during system debugging. Note the following:

- In Columns E through H, the coordinates are displayed only as positive numbers (i.e., the negative sign associated with two of the four quadrants has been stripped out of the NMEA string).
- Column N gives a qualitative indicator of signal quality. Many locations have WAAS differential quality.
- Column V is a toggle that takes on a value of 0 or 1. Each time the user pushes the Push to Capture New GPS Origin button on the home screen (Figure 8), the value toggles from one to the other value. This allows a user to identify, for example, a certain portion of the project that may be different from the rest of the project. The button can be toggled as many times as desired while the program is running, and it will simply keep changing the value back and forth between 0 and 1.
- In Columns P through U, the normal mounting configuration of the three-axis accelerometer orients the Z-axis vertically, the Y-axis horizontally and perpendicular to the rolling direction, and the X-axis horizontally parallel to the rolling direction. In general, the user should expect the Y-axis readings to be small or zero. If the compactor is of a traditional operational design, the X-axis readings will also be small. However, if the design is a tangential or oscillatory type design, both the Z-axis and the X-axis will likely have accelerations more than 1G. When stationary, X and Y will read a low value close to zero and Z will be approximately 1.0G. In an oscillating type compactor, the user can expect to see, for example, values over 4G for Z and over 2G for X. If it is a standard compactor, the values for X will be lower, and if the accelerometer has been attached somewhere that is damped by the suspension system (i.e., the accelerometer cannot be mounted substantially in contact with the ground through the drum in many common compactors), Z will also be lower.
- Column W is used to record more information than Column V. Column V is meant to be a quick way of marking the file without having to leave the home screen. If more detailed comments are needed, the user must switch to the job setup screen (Figure 10 and Figure 11) to make the entry, which will then be entered into Column W. As previously noted, changes on this screen can be made at will and will take effect when entered (i.e., within approximately 1 second).

Table 1. Output Data Format (V2.3).

Column	Data
A	Time stamp—includes date, hour, minute, second (make Excel column wider and format cells to see all)
B	GPS message type (GPRMC)
C	Coordinated universal time
D	Active or void (if "V", GPS signal is lost)
E	Latitude
F	North or south latitude
G	Longitude
H	East or west longitude
I	GPS ground speed in knots
J	Track in degrees from true north
K	GPS date
L	Magnetic variation
M	East or west variation
N	NMEA 0183 V2.30 mode (A=autonomous, D=differential WAAS, E=estimated, N=data not valid)
O	Current temperature (°F)
P	Minimum acceleration in Z
Q	Maximum acceleration in Z
R	Minimum acceleration in Y
S	Maximum acceleration in Y
T	Minimum acceleration in X
U	Maximum acceleration in X
V	New section indicator (0, 1)
W	Comment (alphanumeric)