Data Quality Verification & Sensor Calibration for WIM Systems

Chen-Fu Liao & Gary Davis
Department of Civil Engineering
University of Minnesota

TRB 2012 NATMEC Conference
June 4-7, Dallas, Texas

Acknowledgements

- RITA, USDOT and UMN ITS Institute
- MnDOT – Ben Timerson & Staff in Transportation Data & Analysis
- Sushanth Kumar – Graduate Research Students
- Minnesota Traffic Observatory, UMN
Outline

- Literature Review
- WIM Data Monitoring
- Mixture Model – GVW9
- Cumulative Sum (CUSUM) Methodology
- Analysis Results
- Concluding Remarks

Dahlin, 1992

Recommended 3 measures for WIM quality assurance

1. Class 9 steering axle weights
   - < 32 kips: 8.4 kips
   - 32-70 kips: 9.3 kips
   - > 70 kips: 10.4 kips

2. Class 9 GVW
   - 2 peaks
     - unloaded: 28-32 kips
     - fully loaded: 70-80 kips

3. Flexible ESAL factor
   - compare with “properly calibrated system”
Han, Boyd, Marti, 1995

FHWA-LTPP study

Formal use of statistical quality control methods to monitor WIM systems

Dahlin's 3 classes: unloaded, partially loaded, fully loaded

Presented Shewhart charts for average and range of GVW for unloaded class

Discussed automatic re-calibration
WIM Station 37 (07/17/2010), Lane 1
Shapiro-Wilk Normality Test – QQ Plot

GVW < 32 kips, w=0.964

GVW 32 ~ 70 kips, w=0.503

GVW > 70 kips, w=0.406

Theoretical Quantiles

Ott and Papagiannakis, 1996

Pilot study, connected with NCHRP study of WIM calibration

Investigated using class 9 steering axle weights for monitoring
2 subgroups
< 50 kips and > 50 kips

2 components to variance
“fleet” - estimated from static weight data
“dynamic” - estimated from VESYM simulation
Correction for air resistance effects

Displayed 2 plots of individual steering axle weights
measures falling with 99% CI
measures drifting in/out of 99% CI

“at this time an inexpensive WIM calibration system has not been developed”

Four “most common” statistics to monitor WIM health

- class 9 front axle weight
- class 9 GVW distribution
- class 9 axle spacing
- traffic volume by vehicle class

Traffic Data Editing Procedures, 2002

Pooled Fund Study SPR-2(182)

Described empirical procedure to locating peaks in GVW weight distributions for class 9 & 11

Four ‘Expected Peak’ rules (by lane) – 56, 57, 58, 59
  #56 - unloaded GVW9: 27 - 30 kips
  #58 - loaded GVW9: 72 - 80 kips

  Current estimate of peak central tendency outside specified historical limits
Nichols and Cetin, 2007

- Introduced **multi-component mixture models** to characterize class 9 GVW distribution
- Overall class 9 GVW population consists of several homogeneous, normally distributed, sub-populations
- Used **EM algorithm** to estimate subpopulation parameters

<table>
<thead>
<tr>
<th>Sub-pop</th>
<th>mean</th>
<th>std. dev.</th>
<th>proportion</th>
</tr>
</thead>
<tbody>
<tr>
<td>unloaded</td>
<td>30.9</td>
<td>3.4</td>
<td>0.123</td>
</tr>
<tr>
<td>Partial load</td>
<td>53.3</td>
<td>13.6</td>
<td>0.556</td>
</tr>
<tr>
<td>Full load</td>
<td>76.4</td>
<td>3.1</td>
<td>0.321</td>
</tr>
</tbody>
</table>

Research Focus

- Detecting subtle calibration drifts and other sensor errors
- Mixture modeling using EM technique to model GVW9 distribution
- Formal monitoring using statistical quality control
3 Related Problems

WIM monitoring:
Requires data model characterizing normal operation

WIM diagnosis:
Prior identification of operational modes
Data model characterizing each mode

WIM calibration:
Diagnose mis-calibration
Compute calibration factor
(needed for data adjustment?)

Mixture Model

\[ f(y) = \sum_{i=1}^{n} \lambda_i f_i(y) = \lambda_1 f_1(y) + \lambda_2 f_2(y) + \lambda_3 f_3(y) + \cdots \]

Component Density Function
Mixing Property

Nichols and Cetin, 2007
Mixture Model

Nichols and Cetin, 2007

Mixture Model
Expectation Maximization (EM)

Component | Lower Bound (kips) | Mean (kips) | Upper Bound (kips) | SD (kips) | Proportion
--- | --- | --- | --- | --- | ---
1 - Unloaded | 32.6 | 33.0 | 33.5 | 4.1 | 0.25
2 - Partially loaded | 54.9 | 55.8 | 58.7 | 13.5 | 0.475
3 - Fully loaded | 75.6 | 76.0 | 76.4 | 3.8 | 0.275
Expectation Maximization (EM)
GVW9 Mean with 95% CI

Station 37 Class 9 Lane 2 EM Mean for calibration date 37101210

GVW Mean (kips)

Mean1
Mean2
Mean3
confidence interval

GVW9 Monitoring
Fully Loaded

WIM 37 Lane 1 GVW9 Group 3 Estimation (95% CI)
WIM Station 37  (10/19/2009 ~ 08/10/2010)

Class 9 Daily Steering Axle Weight

WIM Diagnosis
Loadometer Scale

\[ \log_{10}\left(\frac{\text{steering axle load}}{\text{axle space #1}}\right) = a + b \times \log_{10}(\text{axle space #1}) \]
Cumulative Sum
(CUSUM)

- A commonly used quality control method to detect deviations from benchmark values
- Detect small but persistent deviations
- Monitor change detection
- A statistical process control (SPC) tool for quality improvement
- Detect level shifts in auto-correlated noise

\[ C_n = \sum_{i=1}^{n} (X_i - \mu) \quad \quad \quad \quad \quad C_n = C_{n-1} + (X_i - \mu) \]
Adjusting CUSUM

\[ \bar{x}_1 = \frac{\sum_{t=1}^{n_0} \mu_1}{n_0} \quad \bar{x}_{j+1} = \bar{x}_j + \frac{(\mu_{j+n_0} - \bar{x}_j)}{j + n_0} \]

\[ \sigma_j^2 = \frac{w_j}{j + n_0 - 1} \]

\[ w_1 = \sum_{i=1}^{n_0} (\mu_i - \bar{x}_1)^2 \quad w_{j+1} = w_j + (j + n_0 - 1) \left( \frac{(\mu_{j+n_0} - \bar{x}_j)^2}{j + n_0} \right) \]

\[ T_j = \frac{\mu_j - \bar{x}_j}{\sigma_j} \quad p_j = \text{tcdf} \left( T_j, \frac{j + n_0 - 1}{j + n_0}, j + n_0 - 2 \right) \]

\[ U_j = \text{norminv}(p_j, 0, 1) \quad \text{adj.cusum}_j = \sum_{k=1}^{j} U_k \]

WIM Diagnosis

Adjusting CUSUM

Normal Inverse
WIM Diagnosis

Decision Interval

\[ S_0^+ = 0 \quad S_n^+ = \max (0, S_{n-1}^+ + U_n - k) \]

\[ S_0^- = 0 \quad S_n^- = \min (0, S_{n-1}^- + U_n + k) \]

Out of control allowance

\[ k = \frac{5\% \text{ of Average GVW}}{2 \times \sigma} \]

WIM GVW9 Analysis

Fully Loaded (Lane #1)
WIM GVW9 Analysis
Unloaded (Lane #2)

CUSUM Deviation vs. Calibration Adjustment

Calibration Adjustment vs. CUSUM Deviation

\[ y = 0.0046x + 0.0213 \]

\[ R^2 = 0.0113 \]
Summary

- A mixture modeling technique using Expectation Maximization (EM) algorithm
- GVW9, SXW or FXW and FXS were analyzed for 4 WIM stations
- Use adjusting CUSUM methodology for WIM data diagnosis and drift detection together with DI (h) and reference value (k)
- Adjusting CUSUM methodology was able to detect the sensor drifts prior to the actual calibration
- Did not find any relationship between CUSUM deviation and historical calibration adjustment

Ongoing and Future Work

- Better understand current calibration process & procedures
- Validate adjusting CUSUM methodology by select a test site for implementation and compare drift detection with current calibration process
- Quantify the impact of vehicle speed, weather, and pavement condition to the WIM sensors
- Estimate calibration factors
Thank You!

Chen-Fu Liao
Minnesota Traffic Observatory
Department of Civil Engineering
University of Minnesota
(612) 626-1697
cliao@umn.edu