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# Calibration Helps Reduce Disagreement Between Different Pavement Condition Indices

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**Abstract**

To make expert estimates of pavement condition more accurate, the American Society for Testing and Materials (ASTM) split one of the original pavement distress categories, for which experts previously provided a single numerical estimate, into two subcategories to be estimated separately. While this split has indeed made expert estimates more accurate, there is a problem: to get a good understanding of the road quality, we would like to see how this quality changed over time, and it is not easy to compare past estimates (based on the old methodology) with the new estimates, which are based on the new after-split methodology. In this paper, we show that a linear calibration reduced disagreement between these two types of estimates – and thus, leads to a more adequate picture of how the road quality changes with time.

## 1 Formulation of the Problem

**How pavement condition is evaluated: general idea.** To evaluate the pavement condition of a given road segments, experts evaluate several different characteristics of a pavement. These estimates $e_1, e_2, \ldots,$ are then combined into a linear combination $a_0 + a_1 \cdot e_1 + a_2 \cdot e_2 + \ldots$ with appropriate weights $a_i$. This linear combination is known as a Pavement Condition Index (PCI).

The weights are selected in such a way that the PCI can take any value from 0 to 100. The more distresses, the lower the PCI.

Depending on the value of the PCI, the road segments is classified into one of the four categories:

- segments with PCI of 71 and above are classified as *very good*;
- segments with PCI between 51 and 70 are classified as *good*;
- segments with PCI between 26 and 50 are classified as *poor*;
- segments with PCI from 0 to 25 are classified as *very poor.*

This classification helps decide on the priority of road repairs: segments with very poor pavement conditions are repaired first, segments with poor conditions next, and after that, if needed (and if funds are available), some maintenance is performed on good road segments, to prevent their deterioration.

**How pavement condition is evaluated: details.** To standardize pavement condition evaluation, the American Society for Testing and Materials (ASTM) adopted, in 1999, a standard for such evaluation [1]. This standard listed 19 different types of distresses that can be evaluated.

Some of these distresses are important only in certain climates. For example, there are distresses that are important only in cold climates, where ice and snow and freezing are the main reason of road deterioration. Other distresses are important only in hot climates, when asphalt softens because of the high temperatures. As a result, in each geographic regions, only some of the distresses are important – and thus, each region can select appropriate distresses out of the general list provided by the standard.

For example, most California counties selected 7 out of 19 distresses as appropriate for their climate zone; see, e.g., [4]. Because of this selection, the corresponding Pavement Condition Index is usually denoted PCI7. These distresses are also used in many counties with similar climate, including El Paso region where we live.

This list of 7 included a distress called "weathering and raveling" that incorporates two different types of distresses. These distresses are related to the fact that the asphalt – the most frequent top layer of the roads – is formed by aggregate particles (sand, crushed stone, etc.) bounded together by tar (= asphalt proper). Weathering is the wearing away of the tar binder, leaving the aggregate particles in place. Raveling means not only wearing away of the tar binder, but also removing of aggregate particles. In other words, raveling means that the some pieces of the top layer are removed.

In 2009, the ASTM standard was modified, so that weathering and raveling became separate distresses [2]; this separation is preserved in the latest version of this standard [3]. The main reason for this separation is that now, we can use somewhat different weights for these two distresses and thus, get a more accurate picture of the road quality.

Because of this change, the distress identification manual for flexible pavements of the Metropolitan Transportation Commission of California (MTC) was also updated; in the latest edition [5], weathering and raveling are considered two separated distresses. The new Pavement Condition Index is thus based on 8 distresses and is, therefore, denoted PCI8.

**Challenge.** Road maintenance includes not only making immediate decisions about the road repairs, it also includes tracing the road quality year after year – to better understand long-term consequences of different road repair and maintenance strategies. From this viewpoint, for each road segment, it is necessary to have a consistent record of how its quality changed with time.

The problem is that while the previous PCI values were based on the PCI7 standard, the more recent PCI values are based on a different standard: PCI8. The whole purpose of this switch is to make estimates more adequate, so that they better reflect the actual road quality. As a result, for the same road segment, the PCI8 values are, in general, somewhat different from the PCI7 values based on the same expert estimates.

To understand this difference, researchers estimated several road segments based on these two methodologies, and they found out that in some cases, the same road segment is assigned to different categories depending on whether we use the previous standard and categorize the road segment based on the value of PCI7, or whether we use the new standard and categorize the road segment based on PCI8.

For example, one of the California-based comparisons showed that out of 1597 road sections, 51 – more than 3% – were categorized differently by these two classifications. This may sound small, but we need to take into account that road repairs are very costly. For example, to repair raveling, it is necessary to cut and replace the top layer, which may cost more than 1 million dollars per mile. As a result, if we have a reasonably good road segment which does not need to be repaired, and we erroneously classify it as needing repairs, we are wasting a lot of money – money that should be spent to repairing worse-quality road segments. On the other hand, if we erroneously classify a not-very-good segment as not needing repairs, by the next year, this segment will deteriorate even more, and we will need to spend a much larger amount of money to repair the resulting damage. Long-term, it is always much cheaper to repair the roads when they still in reasonably good shape. If we wait until the road becomes really dangerous to vehicles, its repair cost will become comparable with the cost of building a new road.

It is therefore desirable to decrease this disageement between the two Pavement Condition Indices.

## 2 Analysis of the Problem

**What probability distributions should we use.** Expert estimates are not 100% accurate, they are somewhat different from the actual values of the pavement characteristics. Different deviations are possible; large deviations are usually less probable, small deviations are more probable. It is therefore desirable to find out what is the frequency of different deviations, i.e., in mathematical terms, what is the probability distribution of these deviations.

To answer this question, we can take into account that there are many different independent factors that affect the difference between the actual state of the pavement and the expert's estimate. In probability theory, it is known that the distribution of the sum of a large number of small random variables is close to Gaussian (normal) – this follows from the so-called Central Limit Theorem, according to which the distribution of the sum tends to Gaussian when the number of small random components increases (tends to infinity); see, e.g., [6].

Thus, with high accuracy, we can conclude that the distribution of the experts' approximation errors – the difference between the expert estimate and the actual value – is Gaussian.

**What is the relation between two estimates.** Our goal is, given a PCI7 value $X$, to find the most appropriate value of PCI8 $Y$ – and, vice versa, given the value of PCI8, find the most appropriate value of PCI7.

In the same situation, for the same state of the pavement, we may have several different possible values $Y_1, \ldots, Y_n$ of the expert's estimate. We want to find an estimate $y$ which is close to all of them: $Y_1 - y \approx 0$, $Y_2 - y \approx 0$, $\ldots$, $Y_n - y \approx 0$. In other words, we want the multi-dimensional point

$$(Y_1 - y, Y_2 - y, \ldots, Y_n - y)$$

to be close to the point $(0, 0, \ldots, 0)$. By Pythagoras Theorem, the distance between the two points is equal to $\sqrt{\sum\limits_{i=1}^{n} (Y_i - y)^2}$. Minimizing this distance is equivalent to minimizing its square $\sum\limits_{i=1}^{n} (Y_i - y)^2$; this is a particular case of the usual Least Squares method.

To find the minimum, we can differentiate this quadratic expression with respect to $y$ and equate the derivative to 0. As a result, we get $2 \cdot \sum\limits_{i-1}^{n} (y - Y_i) = 0$, i.e., equivalently, $n \cdot y - \sum\limits_{i=1}^{n} y_i = 0$ and $y = \dfrac{1}{n} \cdot \sum\limits_{i=1}^{n} Y_i$. Thus, the optimal estimate of a random variable is its average (mean) value.

Similarly, if we have some prior information, we need to consider a *conditional* mean. In our case, when we know the value $x$ of the random variable $X$ and we want to estimate $Y$, we therefore need to find the conditional mean $E[Y \mid X = x]$.

It is known that for normal distributions, the conditional mean $E[Y \mid X = x]$ linearly depends on known values, i.e., it is equal to $y = a_0 + a_1 \cdot x$ for some $a_0$ and $a_1$; see, e.g., [6]. These coefficients $a_0$ and $a_1$ need to be determined based on the observations. In other words, we need to use linear regression.

# 3 Resulting Models

**Data that we used.** In our analysis, we used databases supplied by several companies. In each database, for several different road segments, we had both PCI7 and PCI8 estimates. Each database contained more than 1,000 pairs of values.

It is known, from previous analysis, that experts from different companies produce slightly different PCI values when evaluating the exact same road segment. The reason for this difference is that, while the companies use the same MTC manual, there seem to be minor differences between companies in training experts.

Because of these known differences, we did not merge the databases into a single one, we analyzed each database separately.

**Typical results.** In all three cases, at first, we simply compared categories corresponding to the PCI7 estimates $x$ and to the PCI8 estimates $y$.

Then, we used the usual Least Squares linear regression to find a linear formula $y \approx a_0 + a_1 \cdot x$, and used the re-scaled values $x' \stackrel{\text{def}}{=} a_0 + a_1 \cdot x$ instead of the original PCI7 values. We then compared the categories based on $y$ with categories based on $x'$.

In all the cases, re-scaling decreased the number of disagreements. For example, for one of the companies, whose database contained pairs $(x, y)$ corresponding to 1597 segments:

- when we compared categories based on PCI8 values $y$ and categories based on the original PCI7 estimate $x$, we got 51 disagreements; in other words, we found disagreement in about 3% of the road segments;
- after re-scaling, when we compared categories based on the PCI8 values $y$ with categories based on the re-scaled PCI7 values $x' = a_0 + a_1 \cdot x$, we found disagreements only in 7 cases, i.e., in less than 0.5% cases.

In other words, without performing any new estimates, just by doing simple calculations, we reduced the number of disagreements by a factor of 7.

For other databases, we also got a decrease – although not as large.

**Resulting recommendation.** Our recommendation is that, instead of directly comparing old PCI7 estimates with the new PCI8 one, a company should:

- first, find the linear regression formula $y \approx a_0 + a_1 \cdot x$ that best reflects the relation between the PCI7 estimates $x$ and the PCI8 estimates $y$ produced by its experts, and
- then, instead of the original PCI7 values $x$, use re-scaled values $x' = a_0 + a_1 \cdot x$ when comparing the old estimates with the new PCI8 ones.

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