Optimizing Highway Funds by Integrating RWD Data into Pavement Management Decision Making

Douglas A. Steele, P.E. (Corresponding author)
Applied Research Associates, Inc.
100 Trade Centre Dr., Suite 200
Champaign, IL 61820

Curt A. Beckemeyer, P.E.
Applied Research Associates, Inc.
100 Trade Centre Dr., Suite 200
Champaign, IL 61820

Thomas P. Van, P.E.
Federal Highway Administration
Office of Asset Management
1200 New Jersey Ave., S.E.
Washington, D.C. 20590

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ABSTRACT

Pavement structural response is an important indicator of pavement structural capacity, which influences performance measures, such as cracking. Traditionally, pavement management systems have tracked performance using condition indices based on visual distress; however, condition indices based on surface conditions only do not provide a measure of pavement structural response, and therefore, an estimate of pavement structural capacity.

The Rolling Wheel Deflectometer (RWD) is an innovative device that efficiently collects network-level pavement structural response produced by an18-kip single axle semi-trailer load traveling at normal highway speeds. This makes the RWD highly productive and eliminates the need for lane closures, which increases the safety and mobility of the traveling public.

Applied Research Associates, Inc. (ARA) collaborated with the Oklahoma Department of Transportation (ODOT) to study the potential benefit of integrating RWD data in their pavement management process. The study included RWD data collection on over 1,000 miles of ODOT highways, processing to determine representative pavement deflections for each Pavement Management System (PMS) section, incorporation of structural index in their decision tree, and generation of rehabilitation plans with and without the structural index to evaluate their effect on management decisions and the optimization of highway funds.

The results showed a significant cost savings when incorporating the RWD-based structural index, primarily due to the use of more cost-effective pavement preservation techniques on pavement sections with good structural response (i.e., low deflections). In addition, the strategy incorporating the RWD-based structural index made better use of funding by delaying treatment on roads with poor structural response until pavement rehabilitation was a cost-effective option.

INTRODUCTION

The RWD is an innovative device to perform efficient structural evaluation of highway networks. It consists of a series of displacement lasers mounted on a custom-designed semi-trailer that collects nondestructive pavement deflections due to an 18-kip single axle load. The RWD operates at normal highway speeds and does not require lane closures or present an interruption to highway users.

By providing a measure of pavement structural response, the RWD helps pavement engineers better assess in-place pavement conditions, more accurately identify pavement remaining service life, and enhance decision making related to pavement repairs. For example, RWD deflection data greatly assist State Highway Agencies (SHAs) in identifying pavements that are in good structural condition and that can be cost-effectively improved by applying pavement preservation techniques rather than using more traditional (and more expensive) pavement overlay techniques.

ARA partnered with the Oklahoma Department of Transportation (ODOT), which has used for many years the dTIMS pavement management software developed and implemented by Deighton Associates, Limited. Working closely with ODOT pavement management staff, the research team collected and analyzed data for approximately 1,000 miles of ODOT's highway network. Using the collected data, the research team then evaluated several potential benefits of incorporating RWD data into ODOT's pavement management activities, including:

- Use of the RWD to replace ODOT's current means for assessing the structural capability of its in-place pavements.

- Enhancement of ODOT's current pavement management process for generating pavement repair strategies.
- Refinement of ODOT's pavement management treatment matrix to incorporate additional pavement preservation/thin overlay treatments options that are supported by the use of RWD deflection data.

The following sections describe the RWD testing program, ODOT's current PMS methodology, and the results of simulations using a modified approach.

RWD EQUIPMENT DESCRIPTION

The RWD uses triangulation lasers attached to an aluminum beam mounted beneath a custom-designed 53-ft semi-trailer. The trailer is sufficiently long to isolate the deflection basin produced by the RWD's 18-kip, dual-tire, single axle from those produced by the RWD tractor. Four lasers work in conjunction to determine the maximum deflection produced by the RWD's 18-kip, dual tire, single axle. Two additional lasers are used to measure the pavement deflection 15 inches forward of the wheels. A climate-controlled chamber maintains the measurement system at a constant temperature. Figure 1 shows an overview of the RWD trailer.

The system includes a distance measuring instrument (DMI) to longitudinally reference collected data, an infrared thermometer to measure pavement surface temperature, and a global positioning system (GPS). In addition to the sensor data, the operator records pertinent topographic information during data collection via customized function keys on the RWD's data acquisition system. This information typically includes, mile markers, bridges, intersections, pavement changes, and so on.

The RWD averages individual deflection measurements over 0.1-mi intervals, providing a mean deflection for use in network-level evaluation. It operates at normal highway speeds and does not require lane closures or traffic control, and therefore is safer and less disruptive to the traveling public than traditional deflection measurement systems.

FIGURE 1 The RWD uses a series of lasers mounted in the passenger wheelpath to measure pavement structural response produced by its 18-kip trailer axle.

TEST SITE CHARACTERISTICS

For this project, ODOT selected approximately 1,000 centerline miles of roadway in Division 5 in the southwestern Oklahoma. ODOT selected the test roads based on their pavement characteristics (primarily asphalt concrete [AC] and composite pavements) and their geographic proximity to each other. The test roads included a mix of functional classifications ranging from four-lane interstates to two-lane secondary and tertiary highways.

Overall, 96 percent of the pavements tested were AC, with the remaining being composite. The breakdown of roadways by traffic volume was 47 percent low, 39 percent moderate, and 14 percent high volume. The majority of roadways had received rehabilitation within the last 5 to 10 years.

In the case of flexible and composite pavement, ODOT determines ride, rutting, functional distress, and structural distress indices. These four indices are used to determine a Pavement Quality Index (PQI) value ranging from 100 to 0 (100=best, 0=worst) for each pavement management unit. In addition, ODOT assigns a base condition rating ranging from 1 to 14 (1=worst, 14=best) for each section based on the subjective judgment of division engineers and FWD testing. ODOT compares FWD data to a standard based on average daily traffic (ADT) for each pavement management system section, rating them as good, fair, or poor. The mean PQI for the roads tested was 91.2, indicating very good condition. The majority of roads had base condition ratings of fair or good. The majority of FWD deflections produced good ratings, based on ODOT's deflection rating method. Interestingly, the FWD deflections did not necessarily correlate well to the subjective base condition ratings, which can be expected, given the inherent differences between the two methods of assessing structural condition.

RWD DATA COLLECTION AND RESULTS

The RWD tested in a single direction on each road, using the direction established for monitoring in ODOT's pavement management system database, and we tested in the outer lane in the case of multilane highways. The RWD tested at normal traffic speeds and averaged approximately 170 test-miles per day, which included several delays for inclimate weather. Following data collection, ARA post-processed raw data files to calculate mean deflections at 0.1-mi intervals and normalized deflections to a standard temperature of 68 °F. Overall, the RWD tested 90 PMS control sections.

For some of the roads, existing FWD deflections were available for RWD comparison. Figure 2 shows an example output of RWD and FWD deflections on the same road collected on different dates. Both data sets have normalized to a temperature of 68 °F to account for temperature differences at the time of testing. The results show the influence of pavement structure and condition on deflection response, with lower deflections indicating thicker, stiffer pavements and higher deflections representing thinner or weaker pavements.

It should be noted that the FWD applied a 9-kip impulse load to a 12-in diameter circular load plate and the deflection shown in figure 2 was measured in the center of the load plate. The RWD applies an 18-kip load to a single axle with dual tires spaced approximately 14 inches apart, center to center, and the RWD sensor measures deflections midway between the two tires. The comparison in figure 2 is not intended to develop a correlation between the two inherently different devices, rather demonstrate that similar structural responses are measured by both.

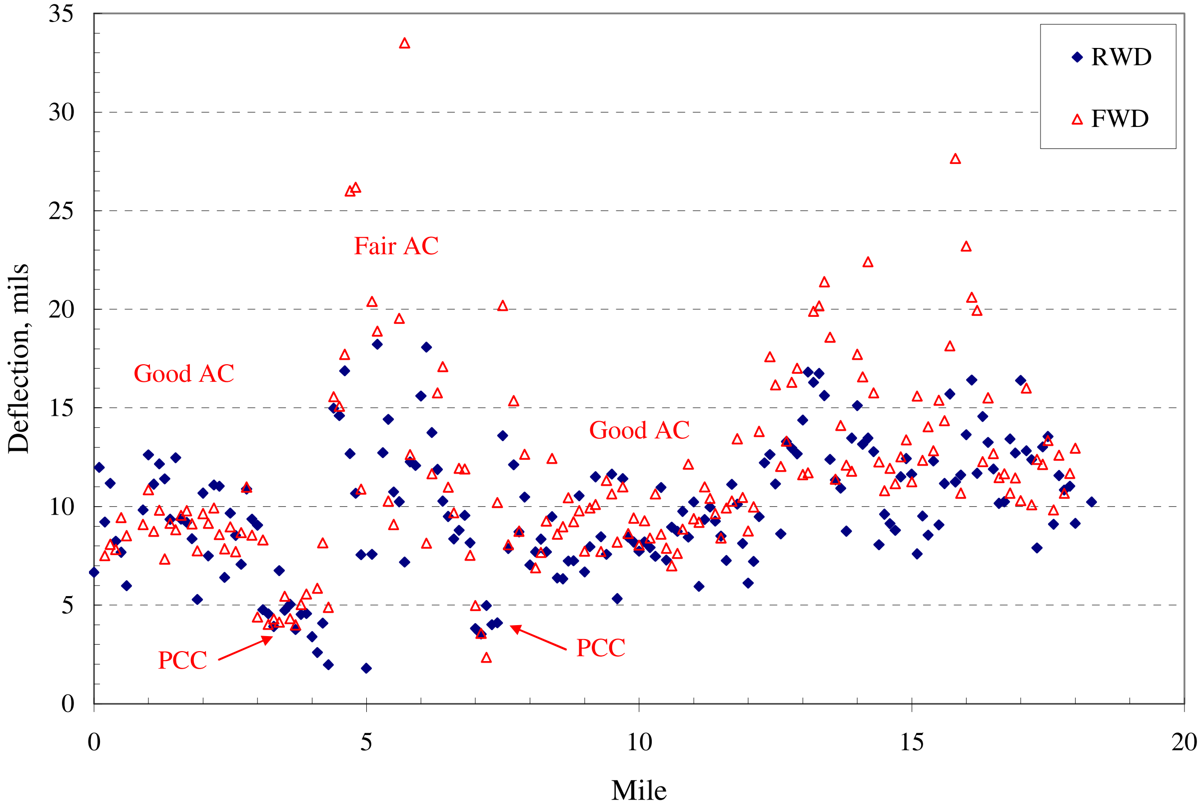


FIGURE 2 Effect of pavement structure and condition on deflection (section 33-04).

ARA calculated the deflection ratio and rating using ODOT's method developed for FWD deflections, which calculates a maximum allowable deflection based on average daily traffic (ADT). ODOT defines structural conditions based on the FWD deflection ratio as:

- Good: <= 1.15
- Fair: >1.15 and <1.5
- Poor: >=1.5

Overall, 72 percent of the sections showed good deflection ratios, while 21 and 7 percent showed fair and poor results, respectively.

For this study, ARA used ODOT's deflection ratio methodology to characterize pavement structure condition, using RWD deflections in place of FWD deflections to calculate the deflection ratio. For the purpose of this study, the two devices were assumed to produce results similar enough in magnitude to determine deflection ratios in the good, fair, poor range. It was not the intent or scope of this study to perform a detailed comparison between RWD and FWD deflections, rather that the inclusion of a deflection-based structural condition factor improves the PMS decision making process and that the RWD makes this feasible for network-level analysis due to its ability to efficiently collect data on large highway networks.

PAVEMENT MANAGEMENT METHODOLOGY

ODOT currently administers its pavement management process using the dTIMS software implemented by Deighton Associates, Limited. ODOT characterizes pavement conditions using a series of performance indices that describe the type and extent of distresses in a pavement, compare condition of different pavement types, and identify the benefits of applying certain treatments to the pavement. The indices currently used to characterize conditions are:

- Functional condition (i.e., surface distress).
- Ride quality.
- Rutting.
- Structural condition.

Each index is on a scale of 0 to 100. The indices are combined to generate an overall PQI, using the following sets of equations:

- AC PQI = 0.4 (Ride) + 0.3 (Rut) + 0.15 (Functional) + 0.15 (Structural).
- Composite PQI = 0.4 (Ride) + 0.15 (Rut) + 0.3 (Functional) + 0.15 (Structural).

Once calculated, the PQI becomes the sole index used by ODOT's pavement management system to select treatment strategies for each pavement management section. To model future performance of its in-place pavement structures, ODOT uses the following equation:

$$PQI = 100 - B * (Age)^2$$

Where,

PQI = Pavement Quality Index (scale of 0 to 100)

Age = Pavement surface age (years)
B = Pavement deterioration variable (ranging from 0.063 to 0.080, depending on pavement type and ADT)

Based on this equation, PQI values are expected to range from approximately 89 to 95 at 10 years (i.e., good to very good condition) and 60 to 75 at 20 years (i.e., fair to poor condition).

ODOT's pavement management methodology also takes into account the pavement's structural condition using a Base Condition Factor (BCF). The BCF is a function of two factors—a subjective Base Condition Rating (BCR) performed by district engineers and the FWD deflection ratio, when FWD data is available. The BCF is intended to flag pavements with poor structural condition for replacement; thereby, preventing pavement preservation or rehabilitation on roads where they will not likely perform well.

ODOT's treatment matrix uses PQI, traffic, and the base condition factor to determine a repair category (e.g., preservation, rehabilitation, and replacement) suitable for a given road. ODOT's PMS determines a repair category (e.g., rehabilitation), rather than specific treatments (e.g., a 3-inch overlay) to simplify the overall analysis process and to give the ODOT divisions more flexibility in prescribing specific pavement repair strategies.

PAVEMENT MANAGEMENT SYSTEM ANALYSIS AND RESULTS

Approach

The research team performed a pavement management system analysis using the two following funding approaches to evaluate the benefit of incorporating deflection-based structural criteria for making pavement management decisions:

- **Target PQI Analysis:** What is the total cost of a multi-year preservation and rehabilitation program to achieve a target network pavement condition, with and without consideration of structural condition?
- **Unconstrained Analysis:** What are the conditions and costs resulting from a multi-year pavement preservation and rehabilitation program with an unconstrained budget, with and without consideration of structural condition?

If inclusion of structural condition results in a more efficient allocation of highway funds, this should be reflected in improved conditions and/or reduced costs.

The research team conducted the analyses using two strategies—ODOT's current pavement management strategy (two scenarios) and a modified set that expands the use of pavement preservation and eliminates pavement replacements triggered solely by structural conditions (four scenarios). In the Current Strategy , the research team compared the current ODOT pavement management strategy with a strategy that evaluates pavement structural condition based solely on RWD deflection (not in conjunction with the subjective base condition factor). The four Modified Strategy scenarios were:

- **PQI Only:** Treatments were assigned based on the PQI ratings only; no structural rating or deflection criteria were considered. In this strategy, pavement preservation is applicable only to low-volume roads.

- **PQI+RWD:** Same as the PQI Only strategy, except that pavement preservation is also applicable for moderate- and high-traffic pavement sections with good structural conditions.

- **Enhanced PQI+RWD:** In this approach, the research team modified the treatment selection criteria to (1) allow pavement preservation for all structural conditions on low-volume roads, (2) allow pavement preservation for good and fair structural conditions on moderate- and high traffic roads, and (3) extend the PQI range for both preservation and rehabilitation of pavements with good structural conditions.

- **Enhanced PQI+RWD, with lower preservation trigger**: Similar to the Enhanced PQI+RWD strategy but lowers the trigger for pavement preservation to PQI = 85 (as opposed to PQI = 88). The research team added this scenario to highlight the potential benefit of a reduced preservation trigger.

Figures 3 through 8 present the decision matrices for each scenario.

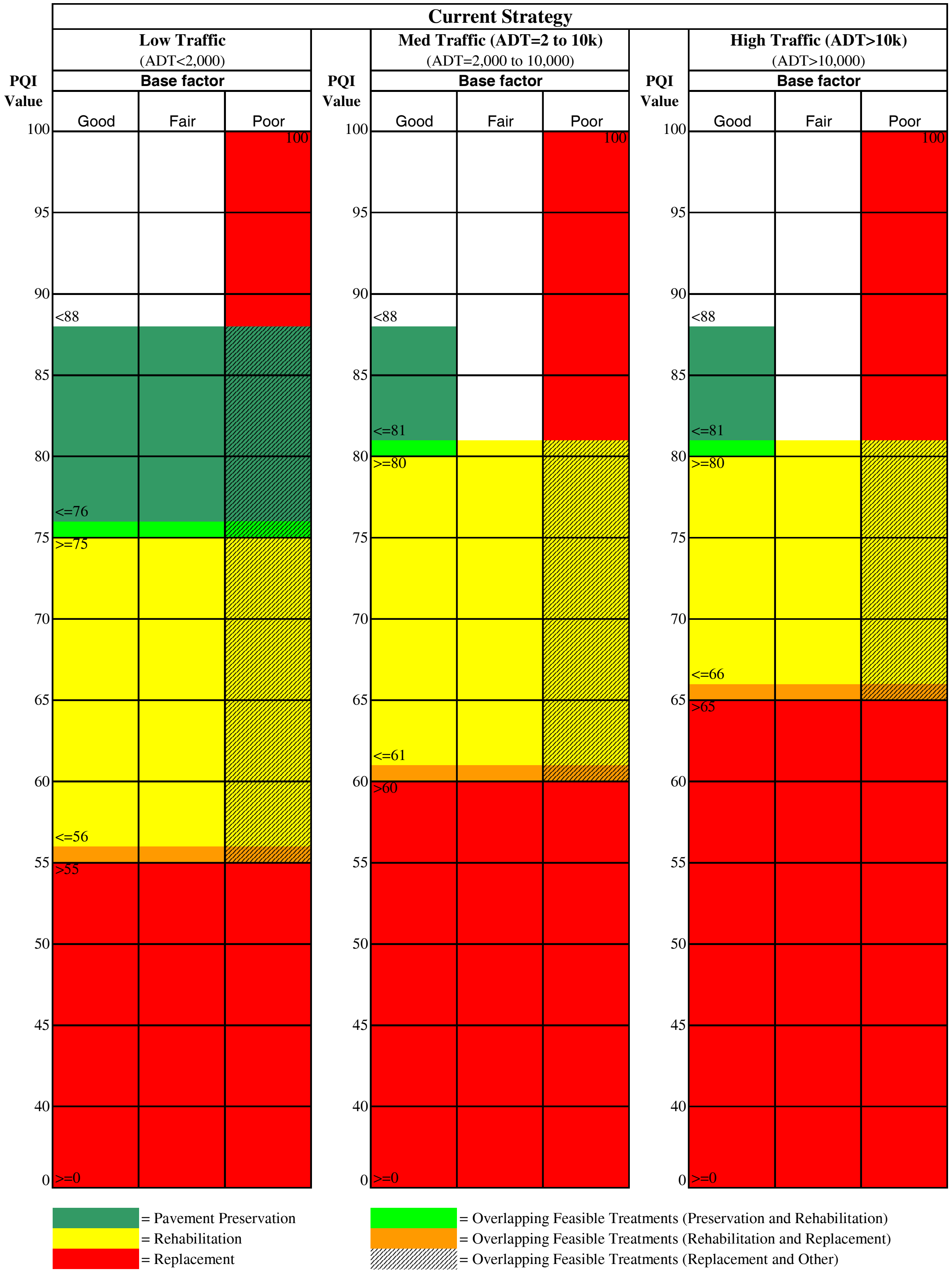
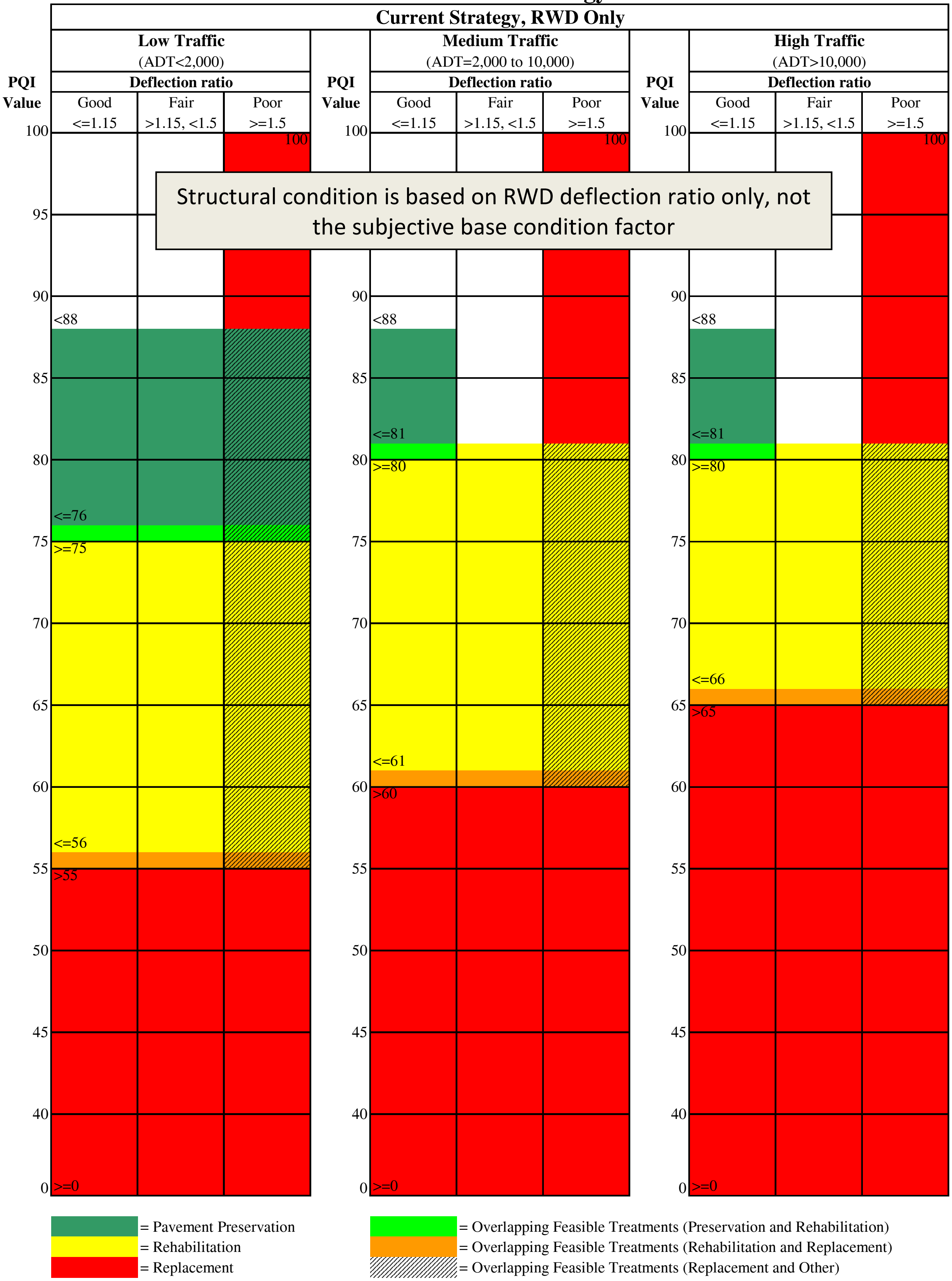

Current Strategy
Low Traffic
(ADT<2,000)
Med Traffic (ADT=2 to 10k)
(ADT=2,000 to 10,000)
High Traffic (ADT>10k)
(ADT>10,000)
PQI Value
Base factor
Good
Fair
Poor
100
95
90
85
80
75
70
65
60
55
50
45
40
0
<88
<=76
>=75
<=56
>55
<=81
>=80
<=61
>60
<=66
>65
>=0
= Pavement Preservation
= Rehabilitation
= Replacement
= Overlapping Feasible Treatments (Preservation and Rehabilitation)
= Overlapping Feasible Treatments (Rehabilitation and Replacement)
= Overlapping Feasible Treatments (Replacement and Other)

FIGURE 3 Decision matrix for the current ODOT strategy.



Structural condition is based on RWD deflection ratio only, not the subjective base condition factor

FIGURE 4 Decision matrix for the current ODOT strategy, but using RWD data only.

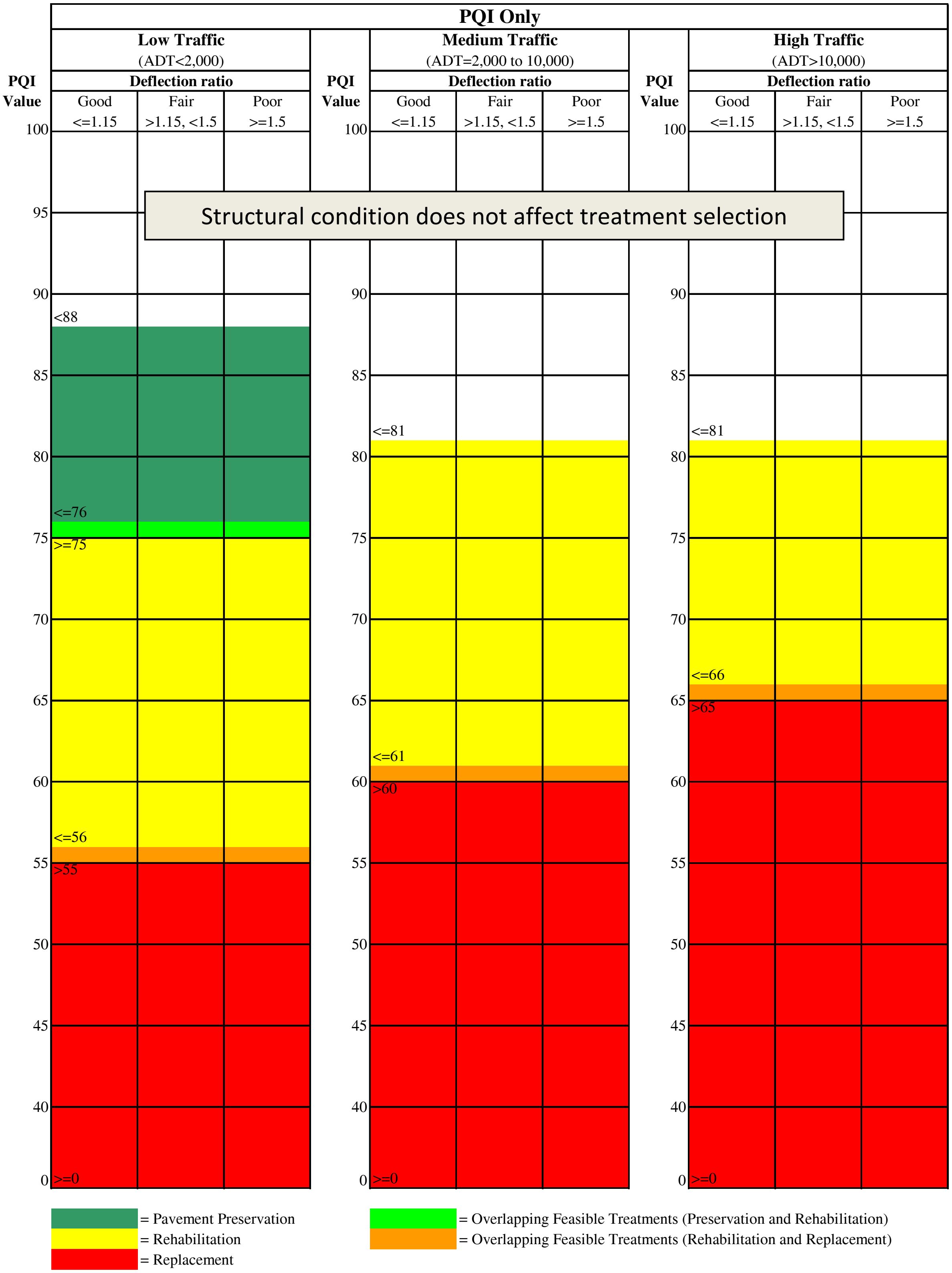
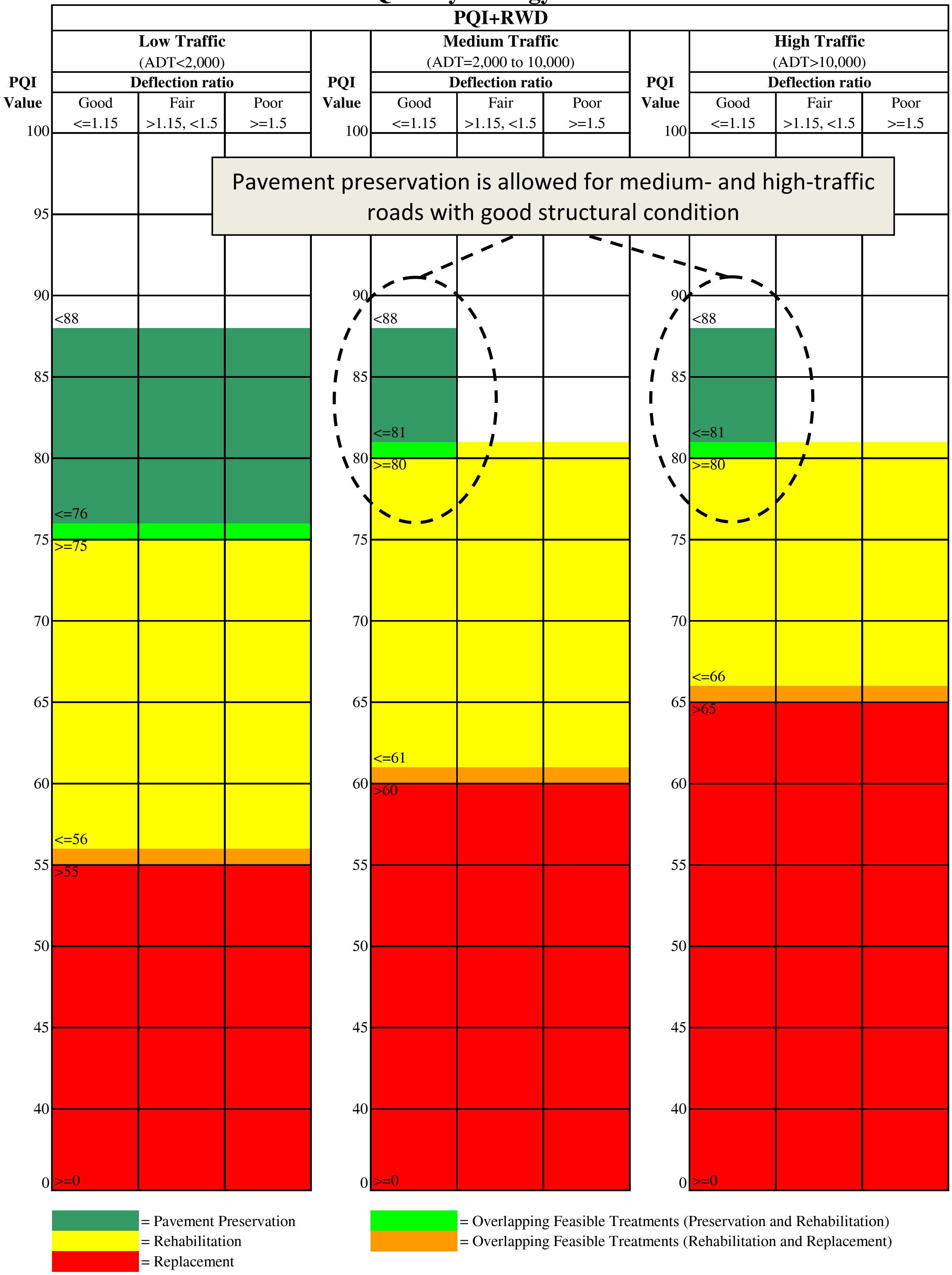
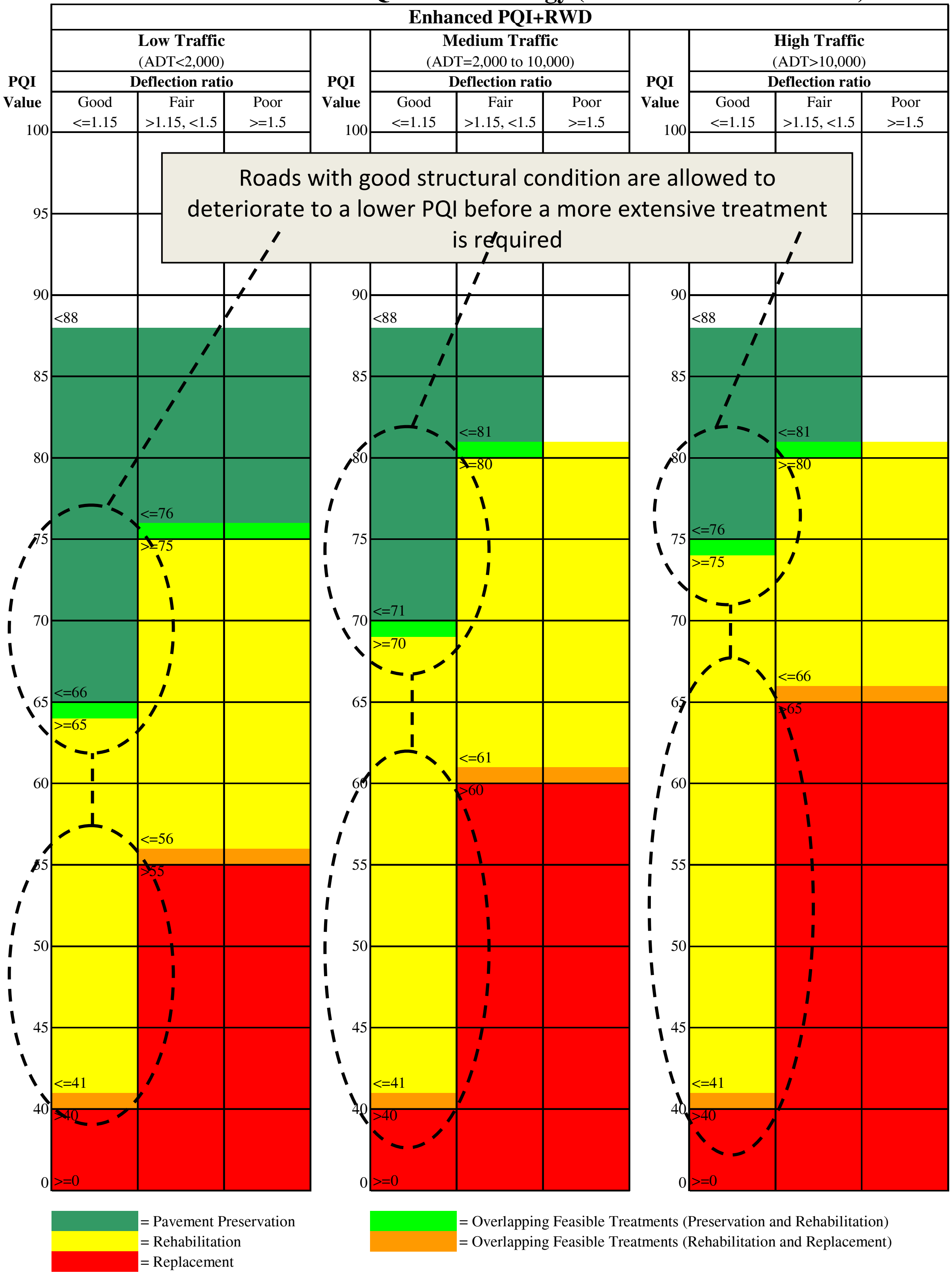


FIGURE 5 Decision matrix for the PQI Only strategy.



Pavement preservation is allowed for medium- and high-traffic roads with good structural condition

FIGURE 6 Decision matrix for the PQI+RWD strategy (ODOT deflection criteria).



Roads with good structural condition are allowed to deteriorate to a lower PQI before a more extensive treatment is required

🟩 = Pavement Preservation
🟨 = Rehabilitation
🟥 = Replacement
🟩 = Overlapping Feasible Treatments (Preservation and Rehabilitation)
🟧 = Overlapping Feasible Treatments (Rehabilitation and Replacement)

FIGURE 7 Decision matrix for the Enhanced PQI+RWD strategy (modified deflection criteria).

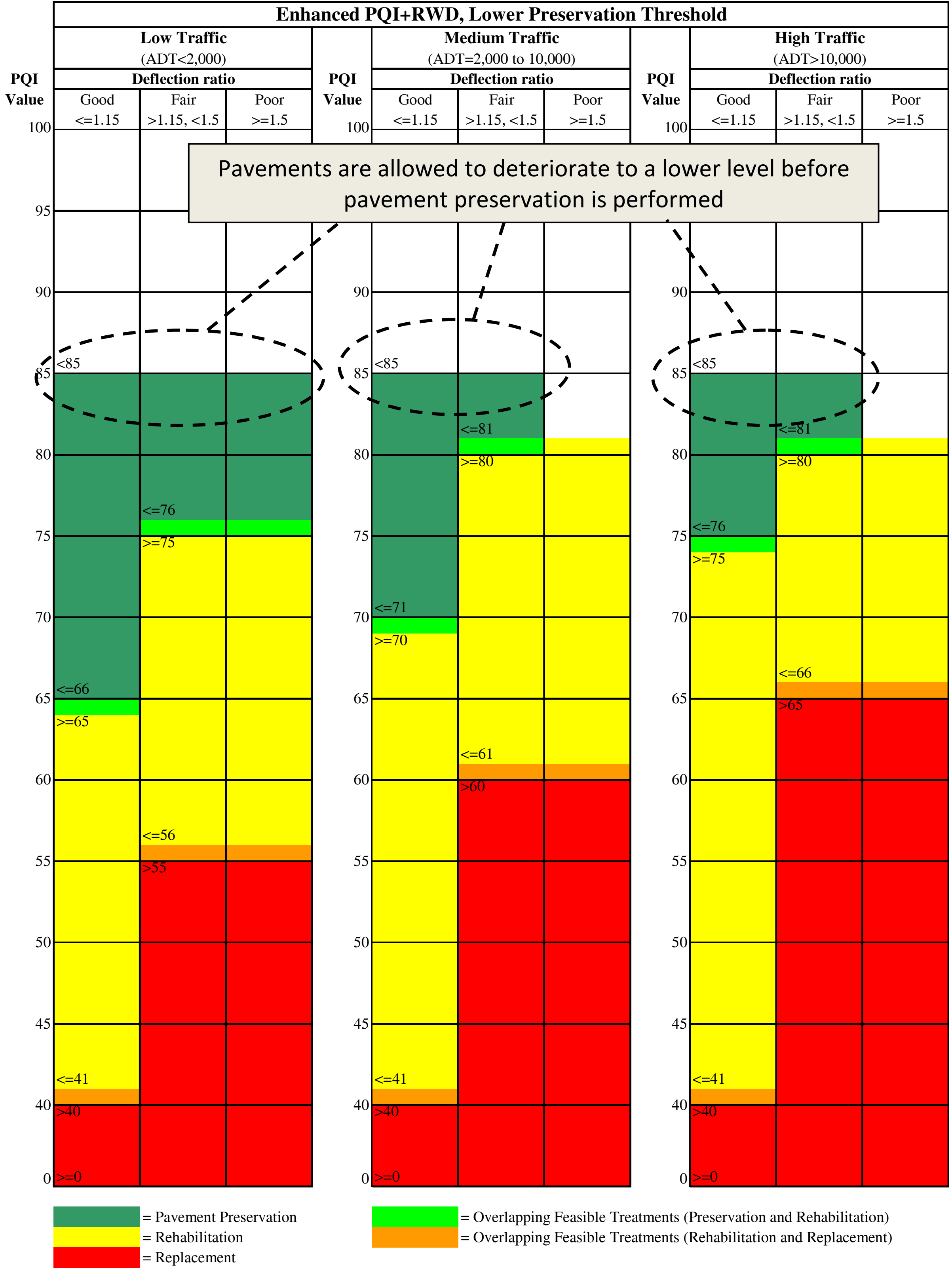


FIGURE 8 Decision matrix for the Enhanced PQI+RWD strategy and lower pavement preservation triggers.

Results

Target PQI Analysis

The research team performed simulations of various treatment scenarios on the 90 PMS control sections included in the study, calculating the funds required over a 20-year analysis period to achieve a network average PQI value of 92 each year, which is the current average condition of the roads tested. The simulations predicted the PQI value for each analysis section based on ODOT's pavement deterioration curves and used this value in conjunction with the traffic and deflection ratio for each section to determine the feasible treatment as determined by the decision matrices presented in figures 3 through 8. For each feasible treatment, the expected benefit, as defined by ODOT's criteria, and the anticipated construction cost were used to determine the benefit-to-cost (B:C) ratio for each analysis sections. The sections were ranked in terms of highest to lowest B:C ratio and sections with the highest B:C ratios were selected until the total network PQI reached the target value of 92. Table 1 presents a summary of results.

Current Strategy The results show that the Current strategy requires an average of $20.64 million per year over the next 20 years to maintain the target PQI of 92. When the subjective base condition rating is eliminated and pavement structural condition is characterized solely by RWD deflections, the required average annual budget reduces to an average of $20.09 million per year, a decrease of 2.7 percent. The change is minor because the current and target PQI values are similar and relatively high, resulting in very few pavement replacements being triggered by the base rating condition. As will be shown later, the base rating factor plays a much more significant role in an unconstrained analysis.

Modified Strategies The PQI Only strategy requires an average of $22.48 million per year over the next 20 years to maintain a network average PQI of 92. By incorporating deflection testing and expanding the application of pavement preservation to moderate- and high-traffic sections with good structural conditions, the cost to maintain a network average PQI of 92 is reduced by 10.6 percent in the PQI+RWD strategy.

Further expansion of the application of pavement preservation provides even greater savings (11.5 percent) as compared to the PQI Only strategy. The expansion adds preservation for moderate- and high-traffic sections with fair structural conditions and reduced PQI thresholds for pavement sections with good structural conditions. Because current pavement conditions are very good and are near the PQI target of 92, this strategy offers only incremental savings over the PQI+RWD strategy. Finally, lowering the trigger for pavement preservation from a PQI of 88 to 85 produces a considerable savings of 20.5 percent compared to the PQI Only strategy. This allows pavements to provide another year or two of service before receiving a preservation treatment, thus greatly reducing the frequency at which preservation is applied.

TABLE 1 Required Annual Budget ($ million) to Achieve an Average Network PQI of 92

Year	Scenario					
	Current Scenarios		Modified Scenarios			
	Current	Current, RWD Only	PQI Only	PQI+RWD	Enhanced PQI+RWD	Enhanced PQI+RWD, Lower PP Trigger
2013	$10.91	$10.91	$10.91	$10.91	$10.91	$10.26
2014	$11.27	$11.27	$11.27	$11.27	$11.27	$11.57
2015	$13.57	$12.57	$12.92	$12.57	$12.42	$11.61
2016	$12.50	$15.01	$11.75	$15.01	$13.81	$12.17
2017	$12.77	$11.37	$12.85	$11.37	$14.63	$15.30
2018	$13.99	$13.99	$16.13	$13.99	$16.67	$12.13
2019	$15.48	$15.81	$20.88	$15.81	$16.05	$14.66
2020	$19.09	$16.66	$17.65	$16.66	$16.53	$15.55
2021	$19.88	$14.91	$22.08	$14.91	$15.92	$12.78
2022	$23.62	$22.28	$26.03	$22.28	$16.46	$15.56
2023	$30.03	$19.22	$25.09	$19.22	$37.88	$14.96
2024	$22.67	$29.44	$33.75	$29.44	$19.51	$28.99
2025	$34.18	$31.18	$26.17	$31.18	$38.45	$38.45
2026	$57.35	$57.35	$37.15	$57.35	$63.36	$61.45
2027	$45.87	$42.10	$16.46	$42.17	$27.89	$20.06
2028	$12.08	$12.08	$26.88	$12.08	$12.08	$4.24
2029	$7.01	$22.85	$13.66	$22.42	$8.81	$19.12
2030	$23.67	$17.17	$21.95	$17.78	$15.37	$9.59
2031	$11.46	$11.74	$52.06	$11.49	$15.52	$14.28
2032	$15.37	$13.93	$33.88	$13.95	$14.17	$14.46
Annual Average	$20.64	$20.09	$22.48	$20.09	$19.88	$17.86
% change from Current Scenario	0.0%	-2.7%				
% change from PQI Only			0.0%	-10.6%	-11.5%	-20.5%

Unconstrained Analysis

The research team performed a second set of simulations with an unconstrained budget over 20 years to compare the average annual costs required to perform all treatments recommended by each scenario in each year. As expected, the results for all six scenarios show very high PQI ratings (from 95 to 97) after 20 years. Table 2 summarizes the results.

TABLE 2 Unconstrained Costs ($ million) to Execute Pavement Treatments.

	Scenario					
	Current Scenarios		**Modified Scenarios**			
Year	**Current**	**Current, RWD Only**	**PQI Only**	**PQI+RWD**	**Enhanced PQI+RWD**	**Enhanced PQI+RWD, Lower PP Trigger**
2013	$149.49	$112.15	$41.42	$46.09	$45.58	$28.41
2014	$19.05	$14.67	$17.56	$15.97	$10.12	$12.69
2015	$7.20	$7.50	$6.95	$7.50	$7.31	$9.83
2016	$11.43	$11.79	$14.44	$14.59	$13.33	$15.72
2017	$10.50	$13.39	$8.42	$13.39	$12.45	$6.19
2018	$28.57	$19.49	$21.77	$19.49	$19.34	$13.08
2019	$5.59	$9.93	$12.12	$9.93	$9.93	$16.23
2020	$12.82	$20.30	$34.50	$24.72	$26.09	$21.02
2021	$21.78	$12.83	$60.26	$12.83	$9.58	$15.97
2022	$18.61	$5.83	$30.66	$8.62	$10.06	$14.31
2023	$50.74	$5.92	$60.81	$10.30	$7.41	$14.21
2024	$12.28	$4.42	$12.50	$4.42	$5.06	$7.40
2025	$5.93	$6.17	$10.51	$6.17	$2.34	$2.22
2026	$2.78	$5.41	$1.86	$5.41	$4.17	$4.15
2027	$36.76	$38.93	$32.44	$38.93	$42.31	$4.01
2028	$30.27	$23.74	$9.99	$19.57	$17.27	$13.83
2029	$14.65	$15.56	$11.22	$15.56	$15.06	$13.23
2030	$7.80	$12.83	$17.20	$14.31	$13.18	$19.79
2031	$24.15	$25.78	$20.33	$25.78	$25.97	$22.17
2032	$11.23	$11.01	$10.18	$11.01	$12.88	$14.52
Annual Avg.	$24.08	$18.88	$21.76	$16.23	$15.47	$13.45
PQI after 20 yrs.	97	97	95	96	96	95
% change from Current Scenario	0.0%	-21.6%				
% change from PQI Only			0.0%	-25.4%	-28.9%	-38.2%

Current Strategy The results show that the ODOT current strategy requires, on average, about \$24.08 million per year over the next 20 years to execute the triggered activities. When the subjective base condition rating is eliminated and pavement structural condition is characterized solely by RWD deflections, the required average annual budget decreases by 21.6 percent. The results highlight the benefit of deflection testing to identify pavements with good structural capabilities, eliminating unnecessary pavement replacement, and justify the use of pavement preservation instead of pavement rehabilitation.

Modified Strategies The PQI Only strategy requires an average of \$21.76 million per year over the next 20 years to execute the triggered activities. By incorporating deflection testing and expanding the application of pavement preservation to moderate- and high-traffic sections with good structural conditions, the average annual is reduced significantly (25.4 percent) in comparison to the PQI Only strategy. The major driver to the cost savings is the use of pavement preservation on sections with good structural conditions (i.e., low deflections).

Further expansion of the application of pavement preservation provides an even greater savings (28.9 percent) as compared to the PQI Only strategy. The expansion adds preservation for moderate- and high-traffic sections with fair structural conditions and reduced PQI thresholds for pavement sections with good structural conditions. Finally, lowering the trigger for pavement preservation from a PQI of 88 to a PQI of 85 produces a considerable savings of 38.2 percent compared to the PQI Only strategy. The use of the lower triggers allows pavements to provide another year or two of service before receiving a preservation treatment, thus greatly reducing the frequency at which preservation is applied.

CONCLUSIONS

The analysis results clearly demonstrated the potential benefit of incorporating network-wide deflection data into the pavement management process. For ODOT’s current strategy, eliminating the subjective base condition rating (which did not necessarily correlate well with FWD deflections) and using RWD deflection as the structural condition indicator:

- Decreased the annual average budget by 2.7 percent in the Target PQI analysis due to a shift toward more cost-effective pavement rehabilitation and preservation treatments, or delaying a treatment until factors other than the subjective base condition rating triggered the treatment. If current pavement conditions were poorer, the savings would be much greater.
- Decreased the annual average budget by 21.6 percent in the Unconstrained analysis. Again, this savings was due to a shift away from replacement treatments that were triggered by the subjective base condition rating to more cost-effective pavement preservation and rehabilitation treatments.

For the modified strategy, the research team compared an approach based solely on pavement surface conditions with approaches that incorporated network-wide deflection testing. The results showed that:

- By incorporating deflection testing for all sections and expanding the application of pavement preservation to moderate- and high-traffic sections with good structural conditions, the average annual cost was reduced significantly (25.4 percent). The major driver to the cost savings is the use of pavement preservation instead of pavement rehabilitation on sections with good structural conditions (i.e., low deflections).
- Further expansion of the application of pavement preservation to include moderate- and high-traffic sections with fair structural conditions provides an even greater savings (28.9 percent) as compared to the PQI Only strategy.
- Lowering the trigger for pavement preservation from a PQI of 88 to a PQI of 85 produces a savings of 38.2 percent compared to the PQI Only strategy. The use of the lower triggers allows pavements to provide another year or two of service before receiving a preservation treatment, reducing the frequency at which preservation is applied.

The analysis results for the specific conditions presented in this study showed that a significant cost savings can be realized by replacing subjective pavement structural ratings with network-level deflection data. Network-level deflection data provide an objective means of quantifying pavement structural condition that allows agencies to optimize the treatment selection and timing to make more efficient use of limited highway maintenance and repair funds. The potential cost savings of incorporating structural condition more than justifies the costs associated with network-level deflection data collection.

ACKNOWLEDGEMENTS

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