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The following changes were made to the document after publication on the Federal Highway Administration website:

Location	Incorrect Values	Corrected Values
Page 12, second column, first paragraph	The suboptimal strategy with the lowest PF value represents the strategy that is expected to have the lowest increase in LCC when compared to the optimal strategy and vice versa.	The suboptimal strategy with the highest PF value represents the strategy that is expected to have the lowest increase in LCC when compared to the optimal strategy and vice versa.

TECH**NOTE**

Remaining Service Interval: A White Paper

FHWA Publication No.: FHWA-HRT-21-006

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WHAT IS RSI?

The remaining service interval (RSI) is a pavement lifecycle–management framework intended to help highway agencies make sound long-term investment decisions. The RSI approach uses one or multiple performance measures as the basis for setting and achieving highway performance goals. The approach can also be used for pavement lifecycle planning (LCP).

WHAT IS THE OBJECTIVE OF THIS WHITE PAPER?

This white paper outlines, in simple terms, the fundamental concepts associated with the RSI framework. The document leads the reader through the basic process of RSI application and uses simple examples to illustrate how the RSI framework can be used to support investment decisions. Additional references are provided to help implement these concepts.

WHAT IS LCP?

LCP refers to the process of developing and comparing strategies "to estimate the cost of managing an asset class or asset sub-group over its whole life, with consideration for minimizing cost while preserving or improving the condition" (CFR 2017, page 224). It assists with the rational evaluation of whether one strategy for maintaining assets is better than another, based on long-term cost and performance considerations (FHWA 2019). For instance, a highway agency's maintenance department could use LCP to decide if LED lights, which have a higher initial cost but longer life, are a better investment than incandescent bulbs, which cost less but have to be replaced more often. Answering this question requires considering all of the costs that will be incurred over the lifecycle of an asset, as depicted in figure 1, and whether or not the established performance goals will be achieved.

WHAT'S THE ISSUE WITH THE CURRENT PMS ANALYSIS APPROACH?

Most highway agencies use pavement management systems (PMSs) to conduct an LCP analysis of their pavement network. While these systems are the best tool agencies have at their disposal today, the analysis approach used in most current PMSs might not produce the most optimal solutions because they typically use a decision tree-based approach. This approach focuses on assessing when the next individual treatment should be applied rather than viewing maintenance as a series of different types of treatments to be applied over the life of a pavement segment at specific times. The decision trees programmed into the PMS are essentially a set of rules for determining feasible treatment options based on pavement type, condition, functional class, traffic, and other factors that are agency specific.

There are two main issues with the decision tree-based approach:

1. **The "true optimal" solution may be missed.** In decision trees, a treatment is triggered based on predetermined thresholds for one or more parameters, such as ride quality (e.g., International Roughness Index (IRI)), overall pavement condition (e.g., Pavement Condition Index), individual pavement distresses (e.g., rutting, fatigue cracking, weathering), and traffic volume. The approach's outcome is a recommended set of treatments that

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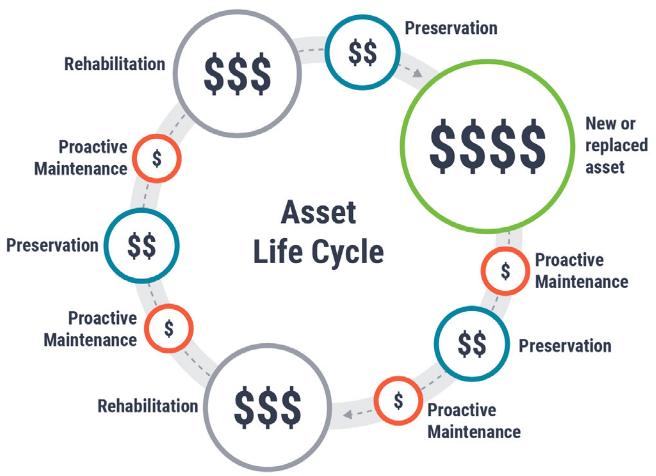
Figure 1. Graphic. Example of an asset lifecycle.



Source: FHWA.

should be applied to each pavement segment in the network that exceeds a threshold over the chosen analysis period. Additionally, if the chosen analysis period is not long enough (≤20 years), several pavement segments might not receive treatment recommendations. The outputs of the decision trees are assumed to be the "optimal" or "near optimal" solutions. However, this assumption may not be true, particularly in the context of a pavement network's whole life. By limiting the analysis to identifying the next treatment based on predetermined thresholds, the approach might fail to account for the economic benefit of investing early or choosing a more substantial treatment. Additionally, in a fiscally constrained scenario that requires prioritizing investments, forcing the use of fixed-treatment trigger rules might cause the true optimal solution to be overlooked.

2. **The LCP analysis may be short-sighted.** As noted earlier, the current PMS analysis approach of focusing only on identifying the next treatment and not on determining a structured sequence of treatments to apply over the lifecycle of a pavement segment is itself a departure from the very definition of LCP. The singular focus on identifying the next treatment action independent of other needs over the life of the pavement segment inherently weighs near-term rather than lifecycle benefits. For a true LCP analysis, the consideration of whole-life costs is essential at both the project and network levels.

RSI CONCEPT—GENERIC EXAMPLE

The differences between the current treatment-selection approach and the approach embodied by the RSI framework can be illustrated with a simple, everyday example involving the maintenance of a car. A car serves as a good example because it has a relatively long service life—if properly maintained—for which there can be many different maintenance strategies, each with different associated costs and levels of risk. The same characteristics also apply to pavements, bridges, and other roadside infrastructure maintenance.

SETTING THE SCENE

Imagine that three individuals who live in the same town bought the same car on the same day. All three consider their car to be in good working condition as long as no unexpected repairs are needed, as evidenced by warning lights or vehicle operation issues. As illustrated in figure 2, each car owner proceeds to utilize a different car maintenance strategy for their vehicle:

- Owner 1 vows to be faithful to the manufacturer's recommended maintenance schedule, assuming this will ensure the longest possible service life with very low risk for unexpected repairs. Among other less routine maintenance activities, this means owner 1 plans to perform oil changes every 3,000 miles or 3 months, rotate the tires every 6,000 miles or 6 months, and adjust the drive belt every 15,000 miles or annually. This approach will cost owner 1 an average of $1,800 annually over a 10-year period.
- Owner 2 is much more guarded, believing that the more maintenance done on the car, the better. Therefore, owner 2 is committed to performing oil changes every 2,000 miles or 2 months and tire rotations every 5,000 miles or 5 months, as well as adjusting the drive belt every 10,000 miles or 9 months. This approach will cost owner 2 approximately $2,200 annually over a 10-year period.
- Owner 3 prefers saving money by deferring maintenance expenditures as much as possible, even if the approach increases the risk of a triggering a warning light or encountering an operational issue. Owner 3 plans to perform maintenance per a "just-in-time" maintenance schedule. The average annual maintenance cost of this strategy is only $600, but when the risk of unexpected repairs over a 10-year period is factored in, the total average annual cost of this strategy is closer to $2,500 per year.

Figure 2. Illustration. Car maintenance strategies.

	OIL CHANGES	TIRE ROTATIONS	BELT ADJUSTMENTS
OWNER #1: MANUFACTURER'S RECOMMENDED MAINTENANCE SCHEDULE Average Annual Cost: **$1,800**	Every 3,000 miles	Every 6,000 miles	Every 15,000 miles
OWNER #2: FREQUENT MAINTENANCE SCHEDULE Average Annual Cost: **$2,200**	Every 2,000 miles	Every 5,000 miles	Every 10,000 miles
OWNER #3: DEFERRED MAINTENANCE SCHEDULE Average Annual Cost: **$600** Average Annual Cost + Unexpected Repairs: **$2,500**	Every 7,000 miles	Every 12,000 miles	Every 30,000 miles

Source: FHWA.

WHICH STRATEGY IS BEST?

Whether any of the owners' maintenance strategies is best is context specific—it depends on what aspects are perceived as most important. All three strategies can potentially avoid warning lights and vehicle operation issues. However, owner 3 has a much higher risk of needing major repairs earlier in the vehicle's life than the other owners due to the longer periods between maintenance.

If an RSI framework were applied to this example, each feasible maintenance strategy would be considered to determine the true optimal solution. Some strategies can be quickly eliminated from consideration because they are not practical or it is readily apparent that the strategy will not be among the potential optimal solutions. For instance, a strategy that suggests replacing the engine each year is an impractical solution. However, there are a considerable number of other combinations of maintenance strategies that might be capable of satisfying the performance goals (i.e., successfully avoiding warning lights and vehicle operation issues). An RSI framework analyzes each feasible strategy and eliminates any that do not meet the established threshold conditions.

The output from an RSI analysis provides owners with a number of strategies to consider when determining how often maintenance is needed. As such, the results allow the owner to better evaluate the potential consequences of deviating from the optimal strategy, since the costs and risks of the less optimal strategies are included in the output. The more comprehensive output information provides a means of better managing household budgets, so they are best geared toward achieving overall performance goals.

Transportation agencies are making the same types of trade-offs on a regular basis. For example, agencies must decide how much to invest in pavements, bridges, and other infrastructure needs (e.g., safety and mobility) because available funding typically is not adequate to meet all demands. Even within an asset class, agencies must determine the optimal allocation between preservation, rehabilitation, and reconstruction needs. As discussed further in this document, the RSI framework provides a data-driven approach that helps agencies make these types of decisions.

RSI CONCEPT—PAVEMENT EXAMPLE

For pavements, the RSI framework is based on identifying a structured sequence of different types of strategically timed repair and replacement measures required to provide the desired level of performance to users over the lifecycle, at minimum practicable costs. For each pavement segment in a network, any treatment type can be applied at any year, provided the established constraints and minimum acceptable level of service (LOS) criteria (e.g., IRI ≤ 170 inches/mile, wheelpath rutting ≤ 0.40 inches for asphalt pavements) are met. The RSI framework is flexible; it allows agencies to use any performance measure to establish LOS criteria and inform other performance constraints. For example, if an agency collects friction information on its pavement network, those data can be used to establish performance constraints requiring maintaining a certain level of skid resistance over a pavement segment's lifecycle.

Establishing LOS Criteria and Other Performance Constraints

The LOS criteria should generally be based on two factors that impact road users: whether the pavement provides a smooth surface on which to drive and whether the pavement structure is safe and minimizes risk. The minimum acceptable LOS criteria can be established based on agency goals and priorities as well as any nationally established performance requirements.

In addition to establishing minimum acceptable LOS criteria, other performance constraints are also established based on engineering logic to determine what treatments are feasible over the pavement lifecycle. Some examples of these constraints include the following:

- Apply a preservation treatment 3 to 5 years after a major rehabilitation treatment.
- Do not apply another major rehabilitation treatment for 10 years once a major rehabilitation is performed.
- Do not apply preservation treatments to pavements in poor structural condition.

Performance Models

For an RSI analysis, it is important for agencies to develop performance models that account for pretreatment pavement conditions (structural and functional). In other words, a treatment applied to a pavment in fair condition would normally be expected to deteriorate at a slower rate when compared to the same treatment applied to a pavement segment in poor condition.

If Any Treatment Can Be Applied at Any Time, Would There Not Be Millions of Possible Combinations?

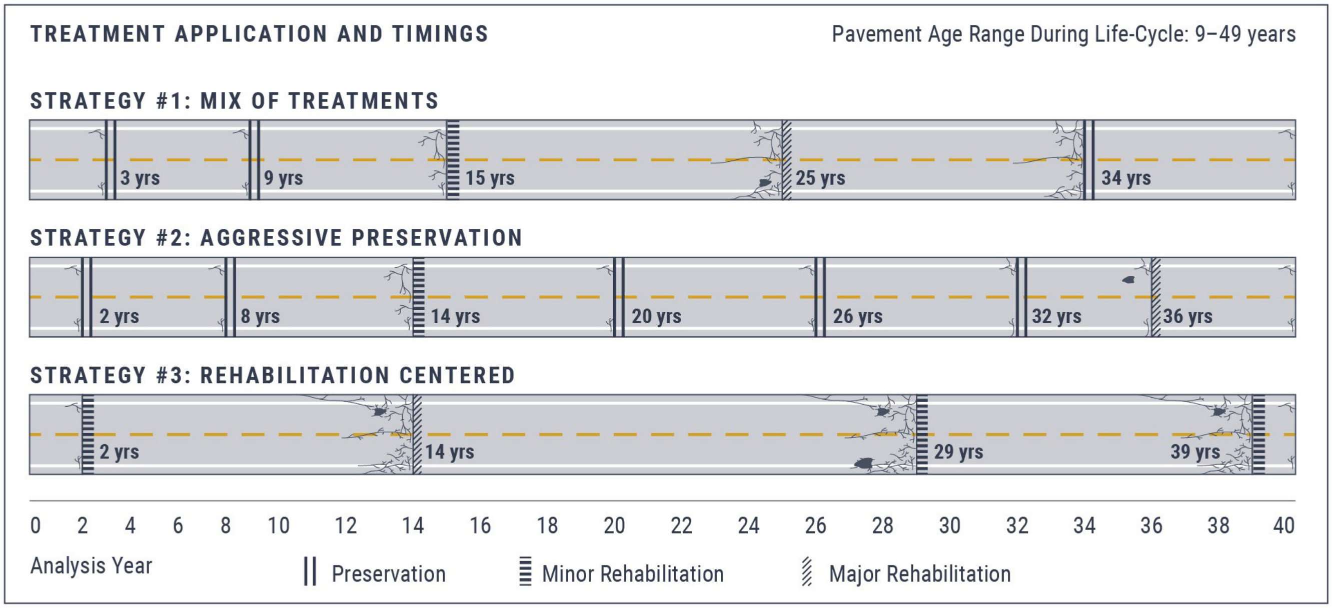
Using this approach, millions of treatment permutations are theoretically possible. With the computing power available today, these options can be evaluated fairly quickly, and several treatment combinations can be eliminated based on a set of common-sense rules. For example, reconstructing a pavement segment every year is one of the possible permutations that will meet the established LOS criteria. This option is not monetarily feasible and will not yield a potential optimal solution, and thus can be eliminated. The final output of an RSI analysis is a structured set of feasible treatment types and timings over a chosen analysis period. Once the lifecycle costs (LCCs) of all feasible strategy options have been evaluated, there will be one strategy with the lowest lifecycle cost (LLCC)—the optimal option—and there will be a number of other suboptimal options with LCCs that are higher than the LLCC.

The process for setting up and performing the calculations can be easily done using a Microsoft® Excel® spreadsheet. The hope is that the next generation of PMS would be able to perform these calculations automatically and the user would just need to make sense of the outputs.

PROJECT-LEVEL RSI ANALYSIS

Let's say an agency constructed three two-lane roadways, each 10 miles long, on the same day in the same town with the same construction materials, design life, and inputs. Each roadway is expected to experience the same amount of traffic and therefore deteriorate similarly. For 8 years, the agency collected traffic and condition data annually on each roadway, and over the course of the 8 years, each roadway received the exact same treatments at the exact same times. Now, 9 years after initial construction, the agency would like to determine the optimal lifecycle strategy to apply to each roadway over the next 40 years using the RSI framework. For the lifecycle strategy to be feasible and meet the minimum LOS thresholds, the agency establishes the following three LOS thresholds, based on the national highway performance measures: IRI ≤ 170 inches/mile, rutting ≤ 0.40 inches, and overall pavement condition = fair or good. The agency then selects and evaluates the impacts of the following three different strategies, illustrated in figure 3 and figure 4:

Figure 3. Illustration. Example of pavement treatment strategy options over a 40-year analysis period.



Source: FHWA.

- **Strategy 1: Mix of treatments.** This strategy follows current asset management practices to determine treatment recommendations. It allows between 6 and 10 years to pass before a treatment is applied and is expected to cost $6.5 million over the 40-year analysis period.
- **Strategy 2: Aggressive preservation.** This strategy proactively applies the application of preservation treatments. It allows no more than 6 years to pass before a treatment is applied and is expected to cost $5.2 million over the 40-year analysis period.
- **Strategy 3: Rehabilitation centered.** This strategy follows historic (worst-first) practices and attempts to defer rehabilitation measures as much as possible. It allows 10 or more years to pass before a treatment is applied and is expected to cost $7.7 million over the 40-year analysis period.

So, Which Strategy Is Best?

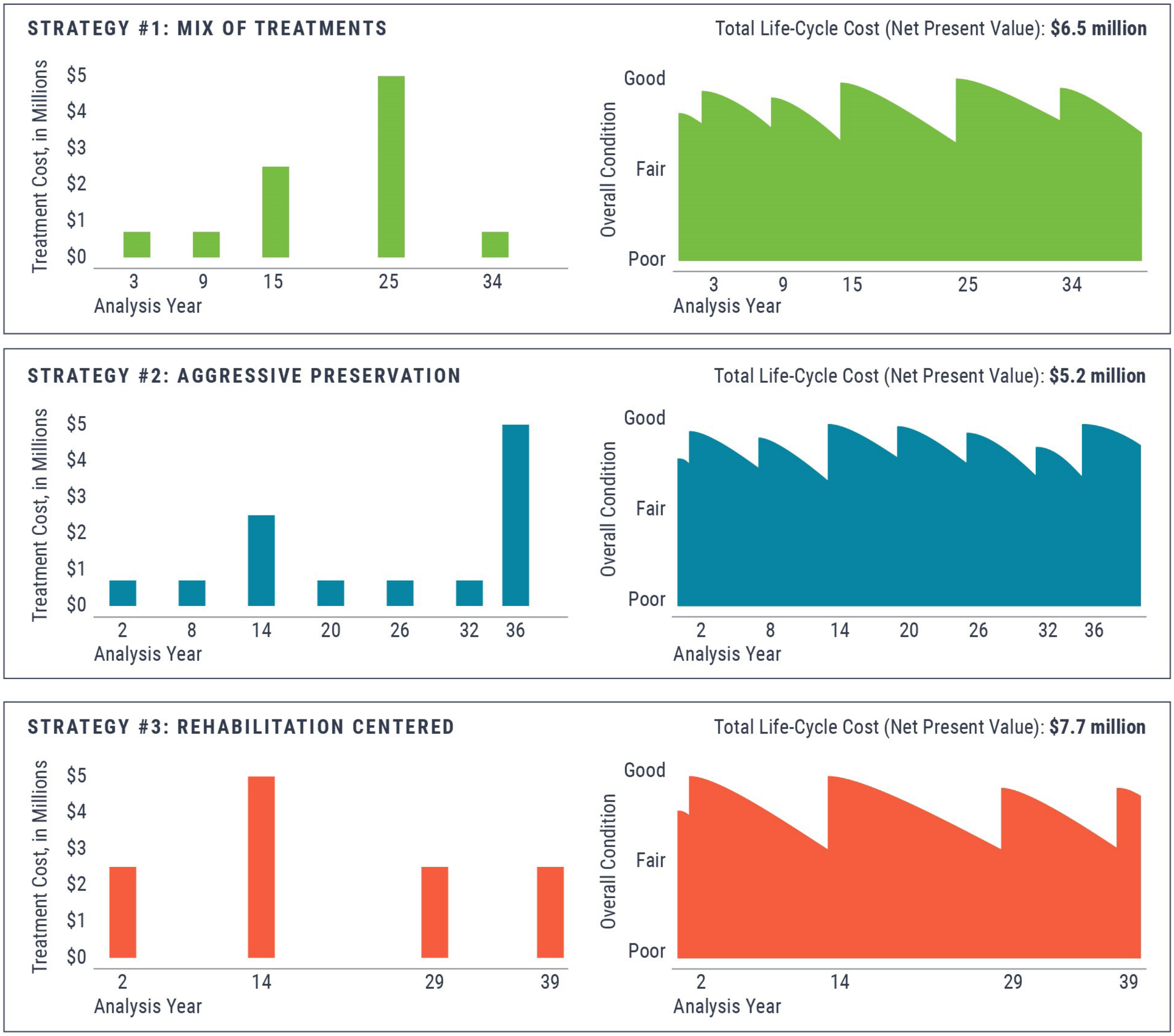
Again, whether one strategy is the best is context specific—it depends on the agency's long-term goals, vision, and resources. Each of the three strategies will achieve the goal of maintaining the established LOS thresholds (IRI, rutting, and overall pavement condition) over the analysis period. Ideally, the agency would like to implement strategy 2, since it results in the lowest cost over the 40-year analysis period. However, the agency must consider a host of other issues before a strategy can be selected:

- Does the agency have qualified contractors that can handle the types of pavement preservation measures the strategy recommends?
- Does the agency have any funding constraints? What if the agency cannot allocate funds for one of the pavement segments until year 3?
- What if the agency needs to divert some pavement funding to other assets and/or programs in a later year?

The example illustrated in figure 3 considered only three strategies. In reality, however, there are thousands of other potential strategies that could be considered. If an agency was able to evaluate all of the feasible strategies using a tool that supports the RSI framework,

Prioritization of treatment strategy in a fiscally constrained environment is particularly important when an agency is dealing with a large pavement network. When funding is limited, the agency may not be able to implement the optimal strategy for each segment in the pavement network, particularly when short-term costs are higher. The goal then becomes identifying the best combination of optimal and suboptimal strategies for every segment in the pavement network that results in the lowest practical LCC for managing the pavement network.

Figure 4. Graph. LCC and pavement conditions for each strategy option.



LOS Thresholds: Rutting and IRI should be kept in Fair or better condition.

Source: FHWA.

Table 1. RSI values.

LCP Strategy	$RSI_{Preservation}$ (Years)	$RSI_{MinorRehab}$ (Years)	$RSI_{MajorRehab}$ (Years)
1: Mix of treatments	3, 9, and 34	15	25
2: Aggressive preservation	2, 8, 20, 26, and 32	14	36
3: Rehabilitation centered	—	2, 29, and 39	14

—No data.

data would be readily available to address some of the trade-off decisions that highway agencies regularly face.

How Is RSI Reported and What Is It Used for?

Asset managers and other agency personnel in charge of maintaining pavement assets can use RSI as a communication metric to convey the year or years in which a particular type of treatment should be applied to meet the established LOS thresholds. $RSI_{Preservation}$, $RSI_{MinorRehab}$, and $RSI_{MajorRehab}$ values are summarized in table 1 for the three strategies depicted in the pavement example (figure 3).

Should the Time Value of Money Be Considered?

The time value of money may not be a critical component of a short-term analysis (<5 years). However, the time value of money should be considered for an RSI analysis because it typically assesses longer analysis periods. The recommended approach is to use real (inflation-excluded) discount rates that are reflective of long-term historical trends. FHWA recommends using long-term real interest rates from the Office of Management and Budget Circular A-94, Appendix C, which are based on Treasury Bill yields and forecast inflation (OMB 2016). Another recommendation is to conduct the analysis using multiple discount rates, so as to understand the sensitivity of the LCC numbers to the discount rates used. Walls and Smith (1998) provide further information on considering the time value of money.

How Is This Not the Same as Conducting a Lifecycle Cost Analysis for Each Segment in the Pavement Network?

While the RSI approach might appear very similar to a typical project-level lifecycle cost analysis (LCCA), there is one significant difference. When conducting an LCCA, the treatment types and timings are inputs to the process. The treatment types and timings to be used for each alternative under evaluation are predetermined (based on historical performance trends and experience or judgment). The user does not consider a set of all feasible treatment types and timings when conducting a typical LCCA.

In contrast, for an RSI analysis the treatment types and timings are outputs of the process. The output of an RSI analysis is a set of all feasible treatment strategy options (treatment types, timings, and associated LCC). As indicated earlier, one of these strategies is expected to be the optimal solution with the lowest practical LCC, and the others will be suboptimal solutions with higher LCCs.

If the RSI Analysis Has Figured Out the Optimal Solution, Why Consider the Other Suboptimal Solutions?

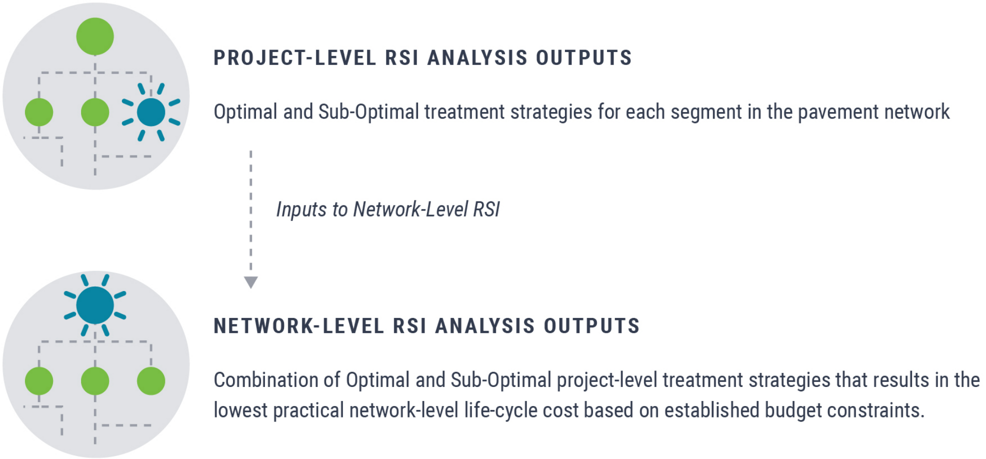
This is a perfect segue into the next dimension of the RSI analysis—network-level RSI application. A financially unconstrained analysis results in one optimal solution and a number of other suboptimal solutions for each pavement segment in the network. While the optimal solution may result in a lower overall LCC, the total investment needed to accomplish the optimal treatment strategy for all pavement segments in the network over the first few years of the analysis may be higher than the funding available to the agency. In such situations, the agency may not be able to implement the optimal strategy for every pavement segment in the network. Based on the funding available, the agency would need to conduct a prioritization analysis to determine the best combination of strategies to apply that would yield the lowest practical LCC at the network level. This concept is explained in the next section.

NETWORK-LEVEL RSI ANALYSIS

In the previous section, the application of the RSI framework at the project level was discussed (i.e., the determination of optimal and suboptimal strategies on a segment-by-segment basis). In the real world, highway agencies need to determine the best strategy for a large pavement network (or a group of pavement networks) that consists of thousands of different pavement segments. This is a network-level optimization problem—the objective is to minimize the network lifecycle cost (NLCC) while ensuring that the established LOS thresholds are met throughout the analysis period. Figure 5 summarizes the key outcomes of project- and network-level RSI analyses.

Meeting the established LOS thresholds has already been addressed under the project-level analysis. Each strategy developed (optimal and suboptimal) for each pavement segment is based on satisfying the LOS thresholds; so this does not need to be considered when conducting a network-level RSI analysis. In a sufficiently funded scenario, the optimal strategy for each pavement segment can be accomplished and will yield the lowest NLCC. However, if a budget is constrained, the main challenge is assessing and prioritizing the various strategies for each segment so as to achieve the optimum mix of strategies that will result in the lowest practical NLCC while keeping total investment needs in each budget cycle within the available funding.

Figure 5. Graphic. Outputs of project- and network-level RSI analyses.



PROJECT-LEVEL RSI ANALYSIS OUTPUTS

Optimal and Sub-Optimal treatment strategies for each segment in the pavement network

Inputs to Network-Level RSI

NETWORK-LEVEL RSI ANALYSIS OUTPUTS

Combination of Optimal and Sub-Optimal project-level treatment strategies that results in the lowest practical network-level life-cycle cost based on established budget constraints.

Source: FHWA.

Recall that for project-level analysis, the focus is on individual pavement segments and which treatments should be applied over the analysis period. When making investments in the near term (≤10 years), different agencies may have different planning timeframes they use to develop their financial plan and investment programs. To keep the analysis approach as flexible as possible, the "planning period" (PP) and the "budget period" (BP) for the network-level analysis need to be defined. The PP is the period that the agency uses for investment planning purposes (such as 5 or 10 years). For consistency, agencies may choose to establish a PP that matches what they use in their transportation asset management plan (TAMP). The BP refers to a shorter period (1 to 5 years) within the PP used to program projects (annual programs, biennial programs, etc.). This range is intentionally chosen to minimize the impacts of the time value of money on the calculations.

A simple conceptual example illustrating the application of the RSI framework to conduct a network-level analysis is presented in appendix A.

Why Are PPs and BPs Needed?

Highway agencies are constantly grappling with the following issues:

- If the optimal sequence of treatments is selected based on a 40-year analysis, how can agencies know if the strategy selected for year 23 (for a pavement segment) today will still be valid 23 years from now?
- How do agencies account for uncertainties associated with funding and long-term pavement performance prediction?

These two situations are precisely why the network-level analysis needs to be assessed in terms of PPs and BPs.

How Is an RSI Analysis Different From What Agencies Are Currently Doing With Their PMSs?

- **Current PMS approaches do not make treatment decisions based on LCCs.** In contrast, the RSI analysis assesses a longer analysis period and evaluates all feasible treatment strategies. The various treatment strategies evaluated will help agencies select the best combination of optimal and suboptimal strategies to also meet established budget and performance constraints.
- **Current PMS approaches do not evaluate the impacts of deviating from the optimal strategy.** The other key distinguishing characteristic of an RSI analysis is the identification of a feasible set of all optimal and suboptimal

> The following is a key question that an RSI analysis can answer (that the PMS analysis does not):
>
> ***How can an agency make the best possible investment decisions today while also ensuring that long-term investments are being optimized?***
>
> The overall goal of the RSI analysis is to help agencies make the best use of available funding in the short term while not losing sight of the whole-life perspective.

treatment strategies for every segment in the pavement network. Current PMS analyses typically provide only one solution. Even if a longer analysis period is selected, the PMS will only provide treatment recommendations based on how the decision trees are setup. However, in an RSI analysis, since all feasible treatment strategy options are stored, the short- and long-term impacts of a number of "what-if" scenarios can easily be evaluated.

- **Current PMS analysis approaches are limited to pavement assets.** The RSI framework can be adapted to analyze nearly any asset that is managed based on the periodic application of treatments to maintain a desired LOS.

WHAT ARE SOME KEY CONSIDERATIONS FOR THE NEXT GENERATION OF PMSs?

The following changes are recommended for the next generation of PMSs:

- **Ability to evaluate the impact of all feasible treatment type and timing combinations and not rely exclusively on decision trees.** As discussed earlier, the use of decision trees to determine treatment recommendations might not always result in the most optimal solution over the long term. If the PMS is enhanced to consider a sequence of treatment types and timings over longer analysis periods and store all feasible treatment type and timing combinations within a master database, the agency can evaluate the impact of a range of lifecycle strategies without having to re-run the same analysis using multiple different sets of inputs/constraints.
- **Ability to calculate LCCs.** Most PMS software tools that exist today do not calculate LCCs. It is imperative that the PMSs are enhanced to be able to calculate LCCs so that an agency can evaluate long-term impacts of different lifecycle strategies.
- **Incorporation of PPs within a longer analysis period.** Agencies typically program projects over a shorter period. However, that does not mean that the agency should lose sight of the bigger picture. If the PMS has the functionality to evaluate lifecycle impacts of decisions made in the PPs, it could help the agency make effective cross-asset trade-off decisions.
- **Use of leading performance measures.** Many of the pavement performance measures used today are based on pavement surface conditions and are "lagging" indicators of investment decisions. A lagging indicator is often easy to measure but is less instructive when it comes to informing decisions that need to be made to achieve goals. Monitoring a person's weight with a scale is a good example of a lag indicator. By monitoring the scale regularly, a person can easily determine whether a target weight has been achieved. However, the measurement of weight alone does not provide any guidance on how to achieve the end result. Two leading indicators, calorie intake and calories burned, are more instructive on how to achieve a target weight. In the same vein, some leading pavement performance measures could include assessing network-level structural pavement condition using traffic-speed deflection devices to project pavement condition. These measures could also include financial performance measures based on asset valuation or planned investments and the resulting impacts of the investments on asset value.
- **Use of performance models that account for pretreatment pavement condition.** As with any pavement management analysis, the key to successfully implementing the RSI framework is using reliable performance prediction models. The next generation of PMSs should have the functionality to develop pavement performance models that account for pretreatment conditions (structural and functional). This can be performed by machine learning techniques that utilize historical pavement condition and construction history information stored in the PMS database.

RSI RESOURCES

The following resources can assist highway agencies with implementing the RSI framework:

- *Pavement Remaining Service Interval Implementation Guidelines* (Elkins 2013). This report discusses relevant terminology and provides a step-by-step process for implementing the RSI framework.
- *Application and Validation of Remaining Service Interval Framework for Pavements* (Rada 2016). This FHWA report demonstrates and further develops applying the RSI framework. The study used real data from two states' PMSs to develop case study examples at both the project and network levels. A summary of this report is also available (FHWA 2016).

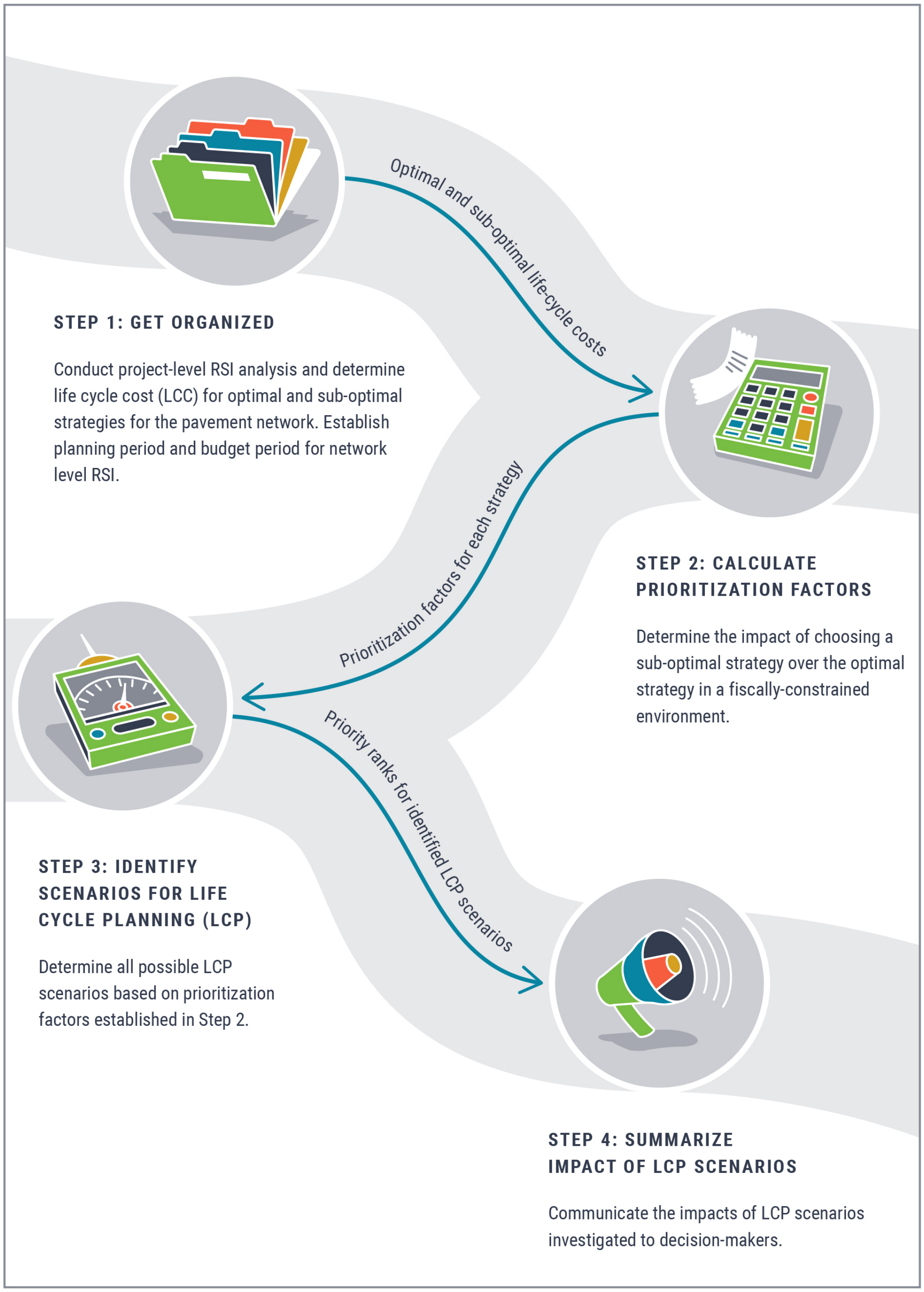
APPENDIX A. EXAMPLE ILLUSTRATING NETWORK-LEVEL RSI ANALYSIS

The network-level RSI analysis can be broken down into four steps, as illustrated and summarized in figure 6. It presents a simple conceptual example that demonstrates application of the RSI framework to conduct a network-level analysis.

Step 1: Getting Organized

The first step is to conduct a project-level RSI analysis for each segment in the pavement network. Next, treatment strategies are grouped into BPs within an established PP, as discussed earlier.

Figure 6. Graphic. Summary of network-level RSI analysis steps.



STEP 1: GET ORGANIZED

Conduct project-level RSI analysis and determine life cycle cost (LCC) for optimal and sub-optimal strategies for the pavement network. Establish planning period and budget period for network level RSI.

STEP 2: CALCULATE PRIORITIZATION FACTORS

Determine the impact of choosing a sub-optimal strategy over the optimal strategy in a fiscally-constrained environment.

STEP 3: IDENTIFY SCENARIOS FOR LIFE CYCLE PLANNING (LCP)

Determine all possible LCP scenarios based on prioritization factors established in Step 2.

STEP 4: SUMMARIZE IMPACT OF LCP SCENARIOS

Communicate the impacts of LCP scenarios investigated to decision-makers.

Source: FHWA.

Consider the following general assumptions for the analysis of a small pavement network that consists of 10 individual segments of varying lengths:

- Analysis period—40 years.
- PP—10 years.
- BP—2 years.
- Discount rate—4 percent.
- Treatment costs (per lane mile)—reconstruction: $1 million; rehabilitation: $500,000, preservation: $200,000.

Since TAMPs typically cover a 10-year horizon (PP), this example looks at the first five BPs (10 years). Even though the focus is on just the first five BPs, the remaining 30 years in the analysis cannot be ignored. To provide further understanding, table 2 summarizes the strategies for just one segment in the pavement network.

In this example, only seven strategies are being considered, with strategy 1 (Opt) representing the optimal strategy and strategies 2 through 7 (SO-1 through SO-6) representing the suboptimal strategies. In practice, however, there could be thousands of feasible strategies that need to be considered in the analysis, all of which ensure that the minimum LOS conditions are not exceeded.

Figure 7 illustrates the comparisons between the various strategies for pavement segment 1. For some investment strategies, a major treatment may lie outside the BPs being considered. For example, strategy 6 shown in figure 7 has the lowest net present value (NPV) of the first five BPs considered; however, it also has the highest LCC. On the other hand, strategy 1—the optimal strategy—has the highest NPV of the first five BPs considered but the lowest LCC. This reiterates the importance of considering the LCCs in addition to the near-term costs (PP costs).

Before getting into the prioritization of strategies, the costs for all of the pavement segments in the network, similar to what is shown in table 2, need to be computed.

Step 2: Calculate Prioritization Factors

Now that the treatment costs in the PPs—in addition to the LCC for each strategy (for each pavement segment in the network)—have been calculated, the next step is to establish a basis for prioritizing between the various strategies to help agencies make decisions in a fiscally constrained environment. The *prioritization factor (PF)* is calculated as follows:

$$PF = \frac{LCC_{SO} - LCC_{Opt}}{NPV_{Opt} - NPV_{SO}} \quad (1)$$

Where:

LCC_{SO} = LCC of the suboptimal strategy.

LCC_{Opt} = LCC of the optimal strategy.

NPV_{Opt} = NPV for all the BPs considered for the optimal strategy.

NPV_{SO} = NPV for all the BPs considered for the suboptimal strategy.

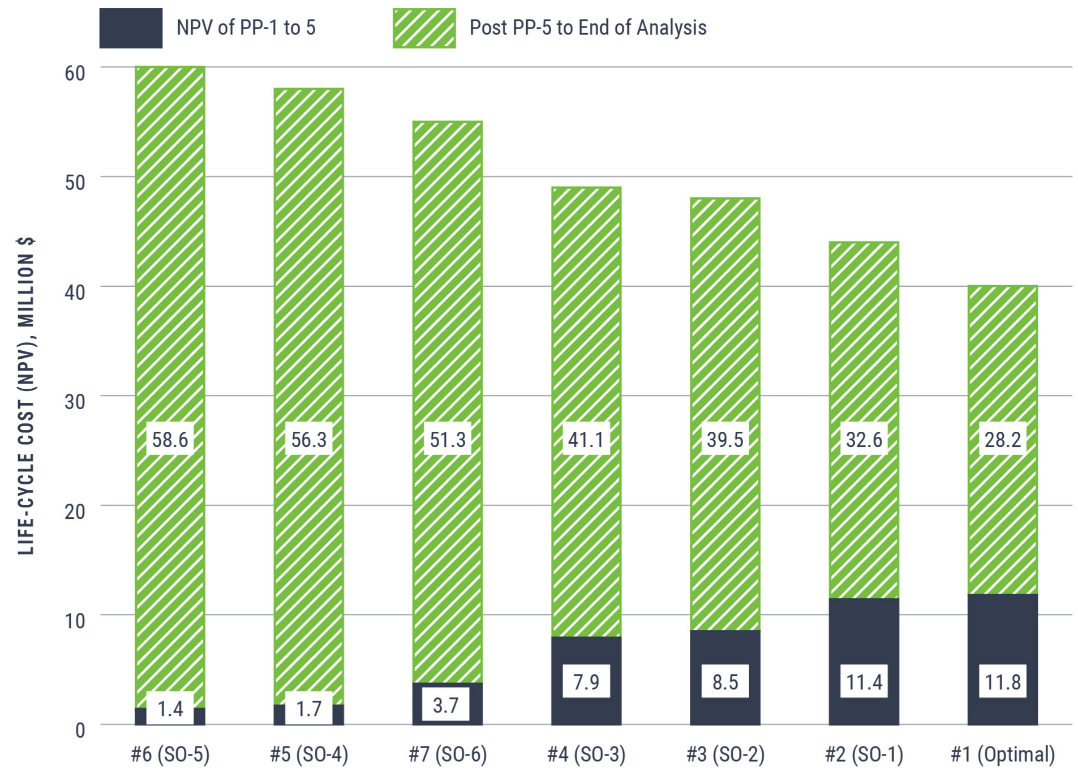
The goal of the PF is to help determine the financial impact of choosing a suboptimal strategy over the optimal strategy for each segment in the network. The PF is used to prioritize the projects that have the highest increase in LCC for every dollar of delayed investment during the PP.

Table 2. Optimal and suboptimal strategies for pavement segment 1.

Strategy	Total Investment of BP-1 Years 0 to 2 (Million $)	Total Investment of BP-2 Years 2 to 4 (Million $)	Total Investment of BP-3 Years 4 to 6 (Million $)	Total Investment of BP-4 Years 6 to 8 (Million $)	Total Investment of BP-5 Years 8 to 10 (Million $)	NPV of BP-1 to BP-5 (Million $)	LCC (Million $)
1 (Opt)	5	—	—	—	10	11.8	40
2 (SO-1)	10	—	—	—	2	11.4	44
3 (SO-2)	—	10	—	—	—	8.5	48
4 (SO-3)	—	—	10	—	—	7.9	49
5 (SO-4)	—	2	—	—	—	1.7	58
6 (SO-5)	—	—	—	—	2	1.4	60
7 (SO-6)	—	—	—	5	—	3.7	55

—BP where no investment was made.
NPV = net present value; Opt = optimal strategy (LLCC strategy); SO = suboptimal strategy.

Figure 7. Graph. Comparison between various strategies for pavement segment 1.



Source: FHWA.

The numerator ($LCC_{SO} - LCC_{Opt}$) is always going to be a positive number because the LCC of the suboptimal strategies will always be greater than that of the optimal strategy. The denominator ($NPV_{Opt} - NPV_{SO}$) can assume positive or negative values and hence the PF can also be positive or negative.

A negative PF value indicates that the total cost of the suboptimal strategy in the PPs considered is higher than that of the optimal strategy. Such suboptimal strategies can be discarded for prioritization purposes since the optimal strategy is the lower-cost option even in the near term.

Suboptimal strategies with positive *PF* values should be considered for prioritization under a constrained budget. In most cases, the *PF* values are expected to be greater than 1.0. Situations in which the *PF* values are between 0 and 1.0 indicate that the higher-cost treatments fall outside the PPs considered. When selecting suboptimal strategies with *PF* values between 0 and 1.0, proper care must be exercised to ensure the treatment plan is appropriate for the period selected.

The *PF* values for pavement segment 1 are summarized in table 3.

The suboptimal strategy with the highest* *PF* value represents the strategy that is expected to have the lowest increase in LCC when compared to the optimal strategy and vice versa. Using the same process step 2 describes, the *PF* values for all the pavement segments in the network are then calculated.

The calculation of the *PF* as discussed in the previous paragraph is just one example of how an agency may choose to prioritize between strategies. There may be other methods of prioritization, and it is not the intent of this TechNote to recommend a method for prioritization.

Table 3. *PF* values for pavement segment 1.

Strategy	*PF*
1 (Opt)	N/A
2 (SO-1)	9.89
3 (SO-2)	2.49
4 (SO-3)	2.34
5 (SO-4)	1.79
6 (SO-5)	1.92
7 (SO-6)	1.85

N/A = not applicable.
Opt = optimal strategy (LLCC strategy); SO = suboptimal strategy.

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*04/07/2021

This paper highlights the importance of the *PF* to assert that agencies should have a data-driven approach for prioritization that considers LCCs.

Step 3: Identify Scenarios for LCP

The next step is to use the calculated *PF* values to develop various scenarios for LCP. The goal of this step is to determine the combination of optimal and suboptimal strategies that results in the lowest NLCC for the established budget constraints (table 4).

Step 4: Summarize Impact of LCP Scenarios

The final step of the network-level RSI analysis is to summarize the information from the analysis for the decision-makers. Table 5, figure 8, and figure 9 illustrate potential formats for presenting the information. Table 5 summarizes the cost (for the five BPs considered as well as the total LCC based on the chosen analysis period assuming similar funding levels as in the PP) of each LCP scenario and presents the pavement network conditions associated with each scenario.

The analysis results (table 5) can also help an agency decide which strategy to implement when budget constraints are applied. For example, if an agency has an average funding of approximately $15 million per BP, scenario E will be the most suitable option to consider. If an additional funding of $5 million per BP becomes available, scenario C will be a better option to consider.

Table 4. Identification of scenarios for network-level LCP (after imposing budget constraints).

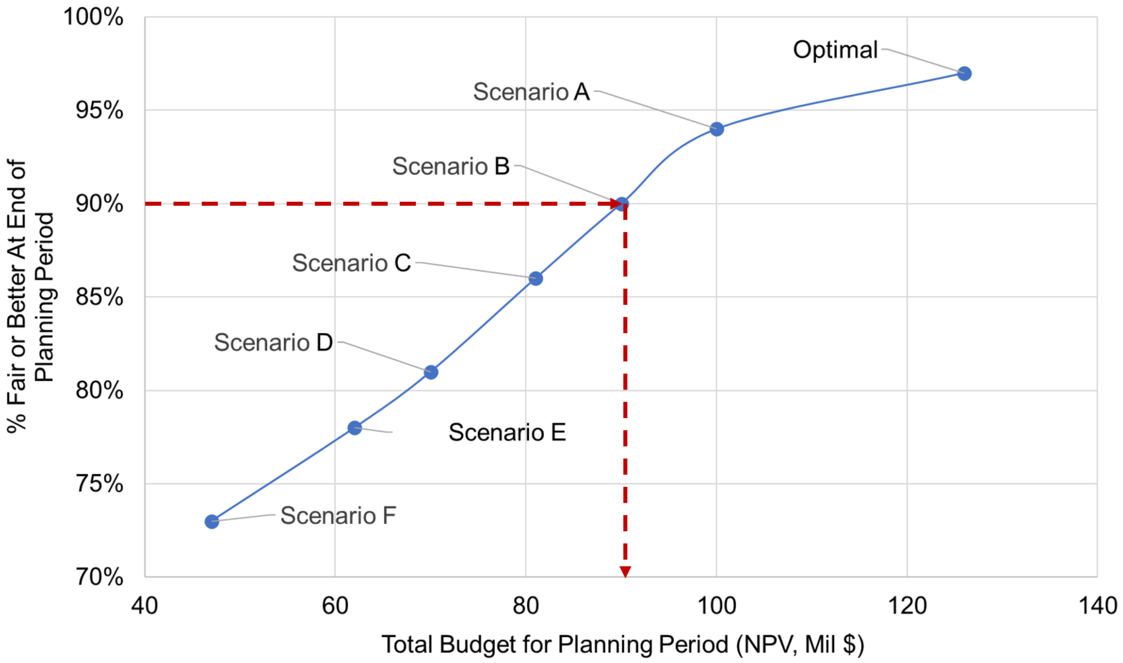
Pavement Segment	Optimal ($31 Million/BP)	Scenario A ($25 Million/BP)	Scenario B ($22 Million/BP)	Scenario C ($20 Million/BP)	Scenario D ($17 Million/BP)	Scenario E ($15 Million/BP)	Scenario F ($12 Million/BP)
1	Opt	Opt	SO-6	SO-5	SO-4	SO-4	Opt
2	Opt	SO-3	SO-3	Opt	SO-3	SO-5	SO-2
3	Opt	SO-1	Opt	So-3	SO-5	SO-1	SO-3
4	Opt	SO-1	SO-4	SO-2	Opt	SO-5	SO-6
5	Opt	Opt	SO-5	SO-4	SO-3	SO-3	Opt
6	Opt	SO-4	Opt	SO-2	SO-4	Opt	SO-2
7	Opt	SO-3	SO-1	Opt	Opt	SO-2	SO-1
8	Opt	Opt	SO-2	SO-4	SO-3	SO-6	SO-4
9	Opt	SO-4	Opt	SO-5	SO-6	Opt	SO-3
10	Opt	Opt	SO-3	SO-5	So-1	SO-5	SO-5

BP = budget period; Opt = optimal strategy (LLCC strategy); SO = suboptimal strategy.

Table 5. Impact of various LCP scenarios.

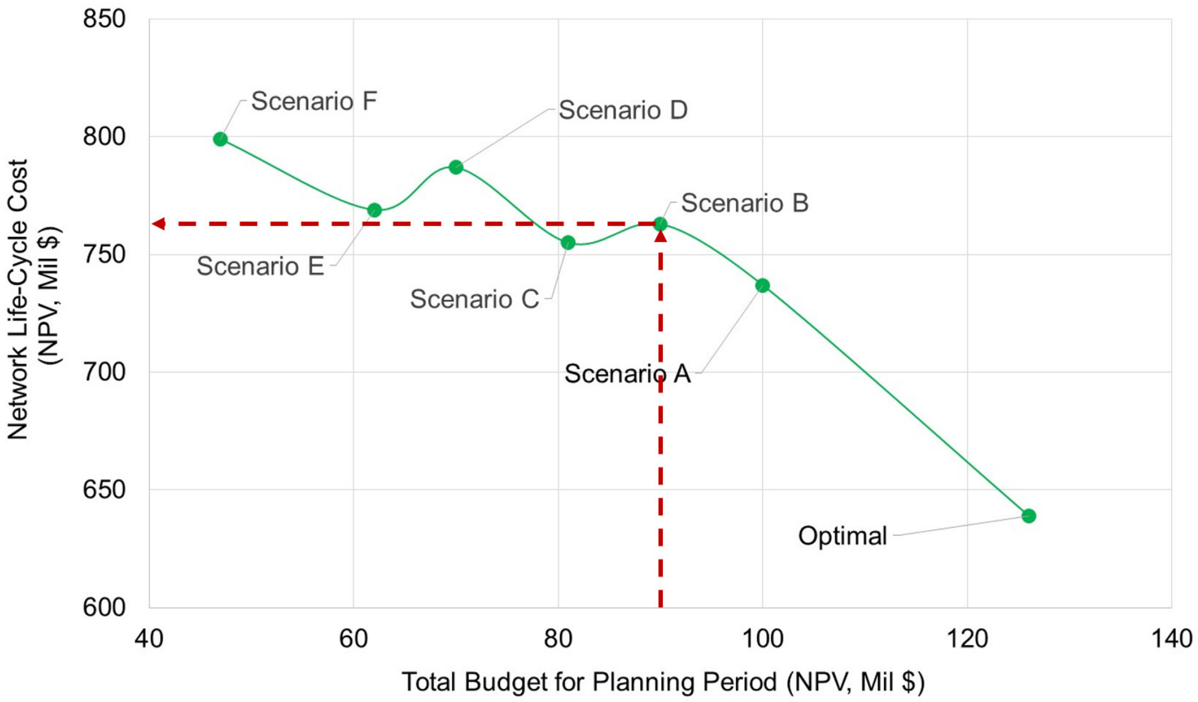
LCP	Cost for BP Number (Million $)					NPV For Five BPs (Million $)	NLCC (Million $)	Network at End of Five BPs		Network at End of Analysis Period	
	BP-1	BP-2	BP-3	BP-4	BP-5			% Fair or Better	% Poor	% Fair or Better	% Poor
Optimal	36	30	30	25	34	127	639	97	3	98	2
A	24	24	24	24	28	100	737	94	6	91	9
B	23	22	22	22	22	90	763	90	10	86	14
C	20	20	20	20	20	81	755	86	14	81	19
D	18	16	16	18	18	70	787	81	19	77	23
E	16	14	16	15	15	62	769	78	22	73	27
F	13	10	12	10	13	47	799	73	27	65	35

Figure 8. Graph. Impact of various funding scenarios on network condition at the end of the PP.



Source: FHWA.

Figure 9. Graph. Impact of various funding scenarios on NLCC.



Source: FHWA.

Figure 8 illustrates the impact of various LCP scenarios in terms of the resulting network conditions at the end of five BPs. This plot can help decision-makers look at the impact on network conditions in the near term (10 years). Figure 8 compares the LCCs for various LCP scenarios against the total cost for the five BPs. While the optimal scenario is the most expensive strategy in the near term, it results in a savings of $160 million (over a 40-year analysis period) when compared to scenario F, which is the least expensive in the near term but has the highest overall LCC.

Using figure 8 and figure 9, an agency can determine the appropriate level of funding required for the PPs considered based on a targeted level of performance. For example, if an agency would like to maintain 90 percent of the pavement network in fair or better condition at the end of the first PP (10 years in this example), the approximate budget required for the PP (five BPs) would be $90 million. This would translate to an NLCC of approximately $760 million over the 40-year analysis period.

If there are situations in which the funding available in each BP is expected to vary significantly, and if that variance is not captured in the different LCP scenarios evaluated, the agency would need to consider evaluating a combination of different LCP scenarios over the BPs. For example, if a funding level of $20 million is available for BP-1, the agency may choose to implement scenario C. If an additional funding of $15 million is available for BP-2 and BP-3, the tool or future PMS analysis modules should be able to consider different funding levels for each BP so as to evaluate the impacts of this particular scenario.

The simple example presented in figure 9 shows six different suboptimal scenarios for a small pavement network with 10 segments. In reality, however, most roadway networks consist of hundreds or thousands of pavement segments, thereby resulting in numerous feasible combinations that need to be considered.

The RSI framework and associated calculations might appear to be relatively complicated when compared to existing practices. The pavement community should work together to consider the merits of truly optimizing treatment decisions with a whole-life perspective when establishing the framework for the next generation of PMSs. The computation cost to implement the RSI framework would be insignificant when compared to the benefits that can be realized by conducting the analysis.

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