Extended Weight Systems Pavement Analysis

Report Number: KTC-22-10/SPR22-57-2-1F

DOI: https://doi.org/10.13023/ktc.rr.2022.10

Kentucky Transportation Center
College of Engineering, University of Kentucky, Lexington, Kentucky

in cooperation with
Kentucky Transportation Cabinet
Commonwealth of Kentucky

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Research Report
KTC-22-10/SPR22-57-2-1F

Extended Weight Systems Pavement Analysis

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June 2022

<table>
<tr><td>1. Report No.
KTC-22-10/SPR22-57-2-1F</td><td>2. Government Accession No.</td><td colspan="2">3. Recipient's Catalog No</td></tr>
<tr><td colspan="2" rowspan="2">4. Title and Subtitle
Extended Weight Systems Pavement Analysis</td><td colspan="2">5. Report Date
June 2022</td></tr>
<tr><td colspan="2">6. Performing Organization Code</td></tr>
<tr><td colspan="2">7. Author(s):
P. Gayle Marks, Jon Wilcoxson, Bryan Gibson</td><td colspan="2">8. Performing Organization Report No.
KTC-22-10/SPR22-57-2-1F</td></tr>
<tr><td colspan="2" rowspan="2">9. Performing Organization Name and Address
Kentucky Transportation Center
College of Engineering
University of Kentucky
Lexington, KY 40506-0281</td><td colspan="2">10. Work Unit No. (TRAIS)</td></tr>
<tr><td colspan="2">11. Contract or Grant No.
SPR 22-57-2</td></tr>
<tr><td colspan="2" rowspan="2">12. Sponsoring Agency Name and Address
Kentucky Transportation Cabinet
State Office Building
Frankfort, KY 40622</td><td colspan="2">13. Type of Report and Period Covered</td></tr>
<tr><td colspan="2">14. Sponsoring Agency Code</td></tr>
<tr><td colspan="4">15. Supplementary Notes
Prepared in cooperation with the Kentucky Transportation Cabinet</td></tr>
<tr><td colspan="4">16. Abstract
Kentucky established its Extended Weight Coal or Coal By-products Haul Road System (EWCHRS) in 1986. This road network includes segments of the Coal Haul Highway System on which more than 50,000 tons coal or coal byproducts were transported by motor vehicles during the previous calendar year. In the past few years, the state has introduced extended weight (EW) systems focused on petroleum products and metal commodities. Trucks can operate above posted weight limits on these networks by paying annual fees that range from $160 to $2,000. While EW networks benefit motor carriers by improving efficiency, vehicles that exceed weight limits can damage pavement and reduce its service life. This study examines the relationship between pavement age and pavement condition on EWCHRS routes and non-EWCHRS routes to understand the implications of EW networks for infrastructure life-cycles. Using data from 2008 through 2020 (with the exception of 2016) to perform regression analysis, researchers found that routes which spent at least 20% of the study period on the EWCHRS saw pavement life decline by 1.5 – 2 years. In general, a positive correlation was observed between exposure on the EWCHRS and loss of pavement life, which can increase maintenance, repair, and rehabilitation costs. While the future of commodity-specific EW networks in Kentucky is unclear, data management strategies can be adopted by the Kentucky Transportation Cabinet to improve its support of existing and future EW networks.</td></tr>
<tr><td colspan="2">17. Key Words
Extended weight, hauling, coal, commodities, pavement condition</td><td colspan="2">18. Distribution Statement</td></tr>
<tr><td>19. Security Classification (report)</td><td>20. Security Classification (this page)</td><td>21. No. Of Pages
36</td><td>19. Security Classification (report)</td></tr>
</table>

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Executive Summary

Kentucky issues special permits and exemptions that let vehicles transporting specific commodities (coal, petroleum, metals) exceed weight limits. In 1986, the state established the Extended Weight Coal or Coal By-products Haul Road System (EWCHRS), which includes Coal Haul Highway System segments on which more than 50,000 tons of coal or coal byproducts were transported by motor vehicles during the previous calendar year. Roads included on the EWCHRS are updated yearly based on coal haul tonnage reports gathered from coal transporters. Vehicles moving coal on the system must display an extended weight (EW) coal haul decal if they meet certain criteria. Operating vehicles above posted weight limits improves efficiencies (i.e. heavier loads on fewer trucks) but can accelerate pavement deterioration. To understand the impacts of EW trucks, this study explores previous research on the relationship between heavy truck traffic on pavement condition and investigates the long-term performance of EWCHRS pavements.

The Kentucky Transportation Cabinet (KYTC) furnished researchers with EWCHRS documentation for 2008 through 2020 (2016 data were unavailable), and information on pavement condition was retrieved from various databases. Data obtained included Pavement Distress Index (PDI) and International Roughness Index (IRI) records. Researchers used EWCHRS data to calculate *Percent EW Exposure* — the measure of length and time a pavement section was part of the system during the study period. Regression models constructed to analyze the relationship between PDI values and pavement age for routes on the EWCHRS and the base system revealed that routes with average annual daily traffic (AADT) counts < 10,000 that spent at least 20% of the study period on the EWCHRS suffered a reduction in pavement life of 1.4 - 2 years, or 11.8-13.2%. Table E1 indicates lost pavement life under six different scenarios of varying AADT and exposure to the EWCHRS.

Table E1 Lost Pavement Life in Relation to AADT and Percent EW Exposure

AADT (Up To)	Percent EW Exposure	Lost Pavement Life	
		Years	%
10k	>10%	1.1 - 1.6	9.3 - 10.2
10k	>20%	1.4 - 2.0	11.8 - 13.2
20k	>10%	0.9 - 1.2	7.3 - 8.0
20k	>20%	1.2 - 1.7	10.1 - 11.3
50k	>10%	0.0 - 0.0	0.0 - 0.0
50k	>20%	0.3 - 0.5	3.0 - 3.4

In the future it is possible Kentucky's General Assembly will need to determine if there is an economic justification for commodity-based EW networks. Permitting trucks carrying exempted commodities to travel above weight limits can hasten pavement deterioration and increase maintenance, repair, and rehabilitation costs. Irrespective of future decisions about EW networks, KYTC can strengthen its ability to support existing EW networks through better data management systems. Several strategies are available to achieve this goal:

- Maintenance data for pavements and bridges need to be available in a geo-located form so that costs can be tied to pavement damage by vehicle type.
- The Pavement Management (PM) Branch retains surface distress data, but comparing one road to another requires looking beneath the surface. Utilizing more comprehensive structural testing will let KYTC examine pavement thickness design loads in greater detail.
- Maintain an electronic database that stores Coal Haul Highway System data
  - The Division of Planning only keeps PDF records of annual EWCHRS data, which hinders data analysis. Electronic documentation will streamline administrative requests and facilitate analysis.
- Expand WIM data collection to EW routes and include truck configurations in AADT

    - Kentucky lacks true AADTT and WIM counts. KYTC cannot document how many trips EW trucks make each day, on which routes, or their weights. The EW petroleum system requires GPS in permitted trucks to map their routes, but this is not required for EW coal trucks.
- There is some ambiguity about when transportation plans need to be filed to ensure districts report damage on roads near mines before KYTC performs engineering analysis. Extensive damage may occur six months prior to KYTC notification. Coal trucks may transport coal on RS routes for a short period (e.g., 6 months) then cease operations. If the cumulative weight of those trucks is less than 50,000 tons annually, the route is not placed on the EWCHRS, despite a significant amount of weight having been transported, including on ramps.

Chapter 1 Introduction and Background

1.1 Background

The Kentucky General Assembly has adopted roadway classifications based on design and function and has set vehicle weight limits to protect pavements and bridges from the damaging impacts of heavy loads. To stimulate economic growth special permits and exemptions have been established that increase weight limits for trucks transporting certain commodities in the state. Kentucky was the first state to establish a commodity-based roadway system that extended standard operating weight limits for trucks hauling a designated commodity. The Extended Weight Coal or Coal By-products Haul Road System (EWCHRS) was established in 1986 and includes Coal Haul Highway System segments on which more than 50,000 tons coal or coal byproducts were transported by motor vehicles during the previous calendar year (see KRS 177.9771). Composition of the EWCHRS is revised each year based on coal haul tonnage reports.

The EWCHRS is made up of discontinuous road segments that vary in length. Vehicles transporting coal on the system must display an extended weight (EW) coal haul decal if they meet certain criteria. In 2019 Kentucky established the Extended Weight Unrefined Petroleum Products Haul Road System and created a route system for trucks hauling metal commodities.

The Kentucky Transportation Cabinet (KYTC) wants to develop better knowledge of the long-term implications of EW networks on pavement conditions (see Marks et al. [2021] for a review of Kentucky's statutes and regulations related to EW limits and permitting and how heavier vehicles impact infrastructure). Initial efforts to discern how EWs impact Kentucky's pavements revealed a wide range of potential costs but that data limitations have hindered efforts to accurately assess the problem.

1.2 Research Objectives

This study examines the impact of heavy trucks on EW systems. KYTC's Division of Planning maintains records of how much coal or coal byproducts are transported on state roads, however, there are limited data on truck traffic counts (i.e., bidirectional trips) and load weights. The Kentucky Transportation Center (KTC) researchers developed a method in this study to compare surface pavement distress of EWCHRS segments that have been part of the system for extended periods to state primary roads with similar AADT. The study period was 12 years, an interval long enough to document the impacts of EW trucks on pavement surface conditions.

Table 1.1 Report Contents

Chapter	Content
2	• Reviews literature on EW laws in other states and Kentucky and the impact of EW systems on pavement conditions and costs • Reviews methods used to investigate pavement traffic and estimated damage costs from heavy truck traffic • Summarizes basic pavement design, pavement performance, and prior studies on pavement damage costs
3	• Reviews Kentucky's pavement management and evaluation practices
4	• Presents the methodology for comparing pavement surface distress of segments on the EWCHRS to the state's primary system
5	• Summarizes findings and suggests areas where KYTC may consider future action

Chapter 2 Literature Review

2.1 Background

While the federal maximum gross vehicle weight (GVW) is 80,000 lb. on interstates grandfathered weight limit laws under the Federal Bridge Formula (FBF) and state weight limit laws permit higher weights, meaning there are no standards for maximum loads among states.

The FBF limits maximum allowable weight on bridges based on number of axles and the distance between axles. States typically set weight limits on roads within their authority and sometimes let local jurisdictions set their own limits. Exceeding weight limits is prohibited unless authorized through special permitting or exemptions. Weight limits that exceed the load carrying capacity of infrastructure produce damage, create safety hazards, and result in costly repairs to pavements.

The Federal Highway Administration's (FHWA) *Compilation of Existing State Truck Size and Weight Limit Laws* (2016) details normal operating weight limits in each state, exemptions, special permits, and routes. Most states issue special overweight (OW) permits for trucks hauling specific commodities. These permits let vehicles exceed normal operating weight limits on non-interstate highways. But weight exemptions for certain routes are not often statutorily defined, and routes are not usually limited by commodity.

Proponents of weight limit exemptions argue they reduce vehicle numbers, trips, and vehicle miles travelled (VMT) while improving cargo efficiency, safety, traffic congestion, and emissions (National Research Council (US) 1990; Luskin and Walton 2001; Adams et al. 2009; Ali et al. 2020). States tout the economic windfalls generated by commodity-based permits as commodities themselves — not permit revenues — help jurisdictions maintain economic vibrancy.

2.2 Standard Weight Limits in Kentucky

Kentucky Revised Statutes (KRS) and Kentucky Administrative Regulations (KAR) establish standard operating GVW limits based on the class of state-maintained roadway (KRS 189.221, KRS 189.222, and 603 KAR 5:066):

- Interstates and AAA: 80,000 lb.
- AAA: 80,000 lb. (with a 5% tolerance except on interstates)
- AA: 62,000 lb.
- A: 44,000 lb.
- Local/County: 36,000 lb.

Truck weight is limited based on the number of axles and their spacing. Maximum GVWs based on axle weight and axle spacing on state-maintained highways (KRS 189.222) are as follows:

- 20,000 lb. per single axle, with axles less than 42" apart
- 34,000 lb. On 2 axles in tandem axles spaced 42" apart
- 48,000 lb. On 3 axles spaced 42" or more apart and less than 102" apart
- No single axle in any arrangement may exceed 20,000 lb. ***Or*** 700 lb. per inch of the aggregate width of all tires on a single axle, whichever is less.

The Secretary of Transportation can increase weight limits and the legislature creates KARs establishing a road classification system with weight limits for each class. 603 KAR 5:066 defines four truck types and GVW limits for each (Table 2.1).

Table 2.1 Kentucky Truck Types and Weight Limits (Tons)

Truck Type	Axles	Roadway Classification			
		County	A	AA	AAA
Type 1	Single unit truck with 2 single axles	18	20	20	20
Type 2	Single unit truck with 1 steering axle; 2 axles in tandem	18	22	27	27
Type 3	1 steering axle; 3 axles in tridem	18	22	31	34
Type 4	Tractor-trailer combination consisting of 5 or more axles	18	22	31	40

Kentucky has several exemptions that typically allow a 5-10% weight tolerance for certain commodities, including agricultural and primary forestry products, livestock and poultry feed, farm supplies, building materials, ready-mix concrete, refuse trucks, and other products. Special permits are available that let trucks carrying coal, petroleum, metal commodities, and other special loads to exceed normal weight limits. KRS 189.269 disallowed new OW/OD permits or tolerances (see Marks et al. [2021] for details).

2.3 Federal and State Weight Limit Exceptions

Several states have grandfathered laws that allow vehicles to exceed weight limits on interstates and/or the National Network (NN).[1] In some cases, states have carved out exemptions that apply to specific routes but not particular commodities. A few states issue OW permits for commodities on specified routes. Wisconsin has many commodity-specific OW permits (e.g., bulk potatoes, forestry products, lumber), many of which include specific route limits. Minnesota issues permits for vehicles carrying special paper products and canola along some state highways. Other states, like Kentucky, Tennessee, and Louisiana, place route limitations on some OW permits for particular commodities, restricting their travel to a limited radius between two points (i.e., port to manufacturing facility, or place of extraction to place of processing).

Kentucky's Extended Weight-Limit Systems

Extended Weight Coal or Coal By-Products Haul Road System (EWCHRS)

On Kentucky's EWCHRS trucks that haul coal can exceed normal weight limits. The EWCHRS includes all state-maintained toll roads, state-maintained roads that were previously toll roads, and public highways on which coal or coal byproducts in excess of 50,000 tons were transported by motor vehicles during the previous calendar year (KRS 177.9771). Each year KYTC revises the system based on data from the previous year. The system includes segments of the Coal Haul Highway System where coal is hauled at normal operating weight limits. Some segments of the Coal Haul Highway System are state-maintained, others are locally maintained.

Each year KYTC publishes a directory of the official coal road system in coal-impact and coal-producing counties (KRS 177.977(1) and KRS 42.455 (7)). The Cabinet also publishes the total centerline mileage of the EWCHRS and ton-miles hauled for each county in the preceding year reported by coal producers or processers that ship or transport coal (603 KAR 5:115).

EWs are automatically assigned when 50,000 tons are hauled on a route in a year at legal weight. The next year individual vehicles can operate with EWs based on the number of truck axles as follows:

- 90,000 lbs. (5% tolerance): 1 steering axle; 2 axles in tandem
- 100,000 lbs. (5% tolerance): 1 steering axle and 3 axles in tridem
- 120,000 lbs. (5% tolerance): Tractor-semitrailer combinations with 5 or more axles
- Potentially unlimited: Motor carriers that meet gross axle weight limits (i.e., 12,000 lbs. for steering axle, 20,000 lbs. per axle.)

[1] https://ops.fhwa.dot.gov/freight/policy/rpt_congress/truck_sw_laws/app_b.htm

Some coal companies enter into cooperative agreements with KYTC to operate on certain roads and fix damages from vehicle activity. Companies have a financial incentive to report all coal hauled as EW trucks reduce the number of trips.

Trucks potentially run OW for short periods on lower class roads. Enforcing weight limits on coal haul trucks poses challenges. Depending on the load, some coal and coal byproducts are denser and therefore heavier than other loads.

Decal fees for EWCHRS-registered trucks go into a dedicated Energy Recovery fund for EWCHRS expenditures. Marks et al. (2021) showed the fund has diminished as the state's coal mining industry has declined. During its early years the state resurfaced significantly more of the EWCHRS than the base system (14.4% vs. 6%) at greater cost ($42,100 per mile vs. $25,700 per mile). Pigman et al. (1995), however, noted the data did not indicate whether the EWCHRS needed more maintenance. Higher maintenance expenditures improved highway rideability in the state's eastern coal-producing counties. While it has been claimed that coal hauling in western Kentucky degraded rideability, data did not confirm that perception. Based on a sample of weight-in-motion (WIM) station data in eastern Kentucky from 1997, Rister et al. (1999) found a large number of EWCHRS-decal trucks hauling over EW limits (88%) and pavement rideability was slightly worse in coal-producing counties than non-producing and impacted counties.

Extended Weight Unrefined Petroleum Products Haul Road System

KRS 177.985 established the Extended Weight Unrefined Petroleum Products Haul Road System. The system took effect in January 2022 and will expire June 2028. Motor vehicles registered with a GVW of 80,000 lb. may carry up to 120,000 lb. with a 5% tolerance of unrefined petroleum on state-maintained highways where 50,000 tons of unrefined petroleum are transported by motor vehicles each year. The annual permit fee is $2,000 and permitted trucks must be equipped with GPS that monitors travel patterns.

Unlike the EWCHRS, permit fees are credited to the Road Fund. Every person, producer, or processor shipping or transporting unrefined products over a state-maintained highway or bridge must report the quantities to KYTC (KRS 177.986). The Cabinet uses these data to calculate ton-miles within each county. Similar to the EWCHS, the Cabinet must publish a directory, supporting maps and documentation, and total county mileage annually and establish administrative regulations for unrefined petroleum transport reporting system requirements and publication of the system.

Metal Commodities Hauling Network

Enacted in 2019, KRS 189.2713 created a route-specific permit that lets motor carriers transport between 80,001 lb. and 120,000 lb. of metal commodities in divisible or non-divisible loads to or from a metal commodities manufacturing or storage facility within the state. KYTC sets approved routes. The annual permit fee is $1,250. When a permit holder applies for a renewal, they must report the number of trips made and total miles driven under the permit during the previous year.

Other States

West Virginia's Coal Resource Transportation System (CRTS)

Beginning in 2003 West Virginia's Coal Resource Transportation System (CRTS) allowed permitted coal trucks to haul up to 120,000 lb. GVW (with 5% tolerance) on public roads, highways, and bridges in 15 of the state's southern counties where 50,000 tons of coal or more were either transported in the previous year or projected to be transported in the upcoming year. Before the system's establishment West Virginia's Department of Highways (WVDOH) recognized that "costly rehabilitation and replacement (of roads and bridges) will be required much earlier than anticipated where heavier loads are imposed on a regular basis" (WVDOH 2002, p. 2; McIlmoil et al. 2010). The agency concluded that increasing the permissible GVW to 120,000 lb. could cut the number of trips by 50% compared to 80,000 lb. trucks but increase strain on roads by 454% (1.24 ESALS for 80,000 lbs. compared to 6.87 ESALs for 120,000 lbs.). Increasing weight limits did not offset the net negative impact to pavements. McIlmoil et al. (2010) wrote:

> The impact of consolidating coal into heavier trucks is somewhat offset by the resulting decrease in the number of trips required to haul the same amount of coal. However, the reduced number of trips falls short of offsetting the impact. The reason is that, given an estimated base weight of a truck of 35,000 pounds, the lighter 80,000 pound truck can carry 45,000 pounds per load, while the heavier truck can carry 85,000 pounds per load. This means that the lighter truck requires approximately twice as many trips in order to haul the same amount of coal as the heavier truck, thereby reducing the number of trips by 50%. By comparison, as noted, the strain on the roads from the heavier truck is 4.5 times greater than that of the lighter truck, so there is a net negative impact on the roads from allowing coal trucks to operate at 120,000 pounds.

West Virginia's CRTS system grew rapidly, with the number of permits issued jumping by 200 each year from 2003 to 2010. Higher construction and maintenance costs have been observed on the system. At the same time most pavement overlays in 2009 were thin, 1.5-inch overlays, more vulnerable to heavy trucks (McIlmoil et al. 2010). Estimated expenditures for the maintenance, repair, and replacement of CRTS roads was nearly $50 million in 2009, while about $17.4 million was spent on bridges.

Virginia's Extended Weights

Beginning in the 1980s Virginia levied severance taxes on coal in seven southwestern counties. The Virginia Department of Transportation started to issue free permits that authorized weight limit exceptions for vehicles exclusively hauling coal from a mine or production site to a preparation plant, loading dock, or railroad. In 1999, HB 2209 increased weight limits to a maximum 90,000 lb. GVW (based on axle configuration) for trucks hauling sand, gravel, or crushed stone within 50 miles in the seven coal severance tax counties. Increases were based on axle configuration, with a maximum GVW of 90,000 lb. for a five-axle truck.

Freeman and Clark (2002) analyzed the pavement condition of roads in the seven coal severance tax counties to roads outside this area to understand the impacts of higher vehicle weights. During the 13-month monitoring period, pavement conditions changed, however, the study was not long enough make reliable conclusions about the differences between roads in the severance tax counties and those elsewhere. Nonetheless roads in the severance tax counties exhibited increases in load-induced distress and wheel path rutting as well as decreased ride quality. Nearly 40% of pavements were structurally inadequate to support the increased weight limits for a sustained period of time. The estimated cost of structural damage to pavements caused by increased truck weight limits was $28 million over 12 years. But this estimate omitted costs related to improving roadway geometry, bridge service life, motorist delays, and safety-related issues for heavy trucks in the mountains.

Energy Boom Cycles Driving Higher Weight Limits

Boom cycles in energy-producing regions can create corridors where OW/OD vehicles operate beyond the capacities of local infrastructure. Several studies have estimated roadway damages in areas with significant oil and gas extraction activities. Methods include estimating the number of heavy truck vehicle trips and calculating ESALs to determine reconstruction costs per lane-mile (Abramzon et al. 2014). In Texas, Quiroga et al. (2012) looked at how energy development affects pavement life data on pavement condition data, inspections and field data. A year after development, they found a new road constructed to support 100 horizontal gas wells would only have 60% of its design life remaining.

Abramzon et al. (2014) estimated highway consumption costs associated with Pennsylvania's natural gas industry, accounting for factors such as permit costs for super heavy trucks, the number of heavy truck trips needed to construct and operate one well, and the loss of road life. They found that roadway life and reconstruction costs are contingent on the number of trips, truck axle configurations, and road type. As the number of truck trips increase, so do consumptive costs. Costs also increased when there were more four-axle single unit trucks than six-axle trucks. However, if trucks used larger roads, expenses declined.

Ashtiani et al. (2019) explored how the impacts of explosive growth in the energy sector (i.e., oil production) in Texas' Permian Basin and Eagle Ford Shale region delayed maintenance and repair activities in several counties where local and state agencies could not meet the unexpected demands of heavy equipment. They developed a new mechanistic approach to quantify the amount of pavement damage from OW trucks tailored to the type of road network, finding a significant loss in pavement life due to increased traffic, especially on local farm-to-market (FM) roads whose base and surface layers are thinner than those on state and US highways. WIM data-collection found trucks over 250,000 lb. on FM roads and 364,000 lb. using state highways within the overload network.

Kentucky's Coal Production and Transportation

Kentucky's coal production is in decline. By 2020 Kentucky had 97 active coal producing mines (U.S. EIA 2020a). These mines produced 24,245 thousand short tons of coal in 2020, a 32.7% decline from 2019. Slightly less than half (42.3%) of the coal produced in Kentucky remains in the state where it is predominantly used by power plants to generate electricity. The rest is distributed to 17 other states (53.4%) or exported to other countries (4.3%). Kentucky's total domestic coal distribution by truck in 2020 was 1,784 thousand short tons — 983 thousand short tons from eastern Kentucky and 800 thousand short tons from western Kentucky (U.S. EIA 2020b, 2020c, 2020d).

The U.S. Energy Information Administration (EIA) provides average annual coal transportation costs by transportation mode. US coal transportation costs fell slightly from 2014 to 2019 while the price of coal decreased more significantly (U.S. EIA 2020e). In the US coal is mostly shipped via rail. Although more expensive than transporting coal by barge or truck, rail shipments are more cost-effective because trucks and barges do not haul as much volume at one time. Coal trucks are primarily used to move coal on shorter intrastate routes. Across the US truck coal freight declined considerably more than other transportation modes in 2019 (down 13%).

Kentucky's Petroleum Production

Half of Kentucky's counties have oil-producing wells. The state has one operational oil refinery that processes crude oil (US EIA 2021a, 2021b). It is the 14th largest oil refinery in the U.S. (with 1.6% of U.S. refining operating capacity) and accounts for about 0.1% of the country's proved crude oil reserves and production. Despite increased oil production in 2019, production declined in 2020 due to less demand and lower costs during the COVID pandemic (US EIA 2021c).

Federal Pavement Reporting Requirements

Federal law requires States to maintain a pavement management system (PMS) and report pavement condition and performance measures each year to FHWA for the National Highway Performance Program (NHPP). Measurement requirements are detailed in *National Performance Management Measures for Assessing Pavement Condition*, 23 CFR 490 Subpart C. FHWA uses the Highway Performance Monitoring System (HPMS) database to assess National Highway System (NHS) roadway performance on a good/poor scale. States must report pavement distress measures for roughness, cracking, and rutting (asphalt pavements only), faulting (concrete pavements only), and serviceability ratings (PSR) (for roads with speed limits less than 40 mph) on NHS roadways. States with more than 5% of their interstates rated in poor condition forfeit a percentage of NHPP and Surface Transportation (STP) funding for interstate repair. In the 1999 Governmental Accounting Standards Board Statement 34 (GASB-34) *Basic Financial Statements—and Management's Discussion and Analysis—for State and Local Governments* FHWA established annual financial reporting requirements for state, local, and municipal governments.

2.4 Costs of Increasing Truck Weight Limits

Multiple studies have investigated the relationship between increasing vehicle weight limits and infrastructure damage. In the early 1990s the New England Surface Transportation Consortium (NETC) found that OW trucks exceeding legal weight limits cause more damage than trucks operating legally (Oliverira 2014). Montana investigated the economic impacts of increasing truck weights under four scenarios: maximum GVWs of 80,000 lb., 88,000 lb., 105,500 lb., and 128,000 lb. (Hewitt et al. 1999). At the time there were limited changes to highway infrastructure performance ($ 1.5 million). The study predicted new traffic streams would emerge under new truck weight scenarios and that heavy truck traffic would decrease, although carriers would operate heavier trucks. Vehicle miles travelled (VMT) decreased nominally under the 128,000 lb. scenario. Increasing limits to 128,000 lb. from long combination axle load limits with maximum GVWs based on FBF (leading to limits of 114,000 to 123,000 lbs. on 7-9 axle combination vehicles) increased pavement demands by 1.5% (equivalent single axle load [ESAL] miles of demand) and increased annual pavement costs by 0.6%.

Changing Heavy Truck Traffic and Impacts to Pavements

Roads degrade faster with greater exposure to higher GVWs, heavier loads, and some axle loads (Dey et al. 2014). While the number of OW and exempted trucks is low relative to other vehicle traffic, they inflict a disproportionate amount of infrastructure damage. This reduces pavement and bridge service lives and increases maintenance, rehabilitation, and reconstruction costs. Pavement distress (e.g., rutting, cracking, fatigue) due to heavy vehicle traffic can also pose safety hazards. Increased pavement roughness drives up fuel consumption and operating costs (Sime et al. 2021). Many states report permit fees are insufficient to cover the cost of using roadways, based on disproportionate infrastructure damage from heavy vehicles.

Although studies have looked at how loads influence infrastructure damage and costs, few have assessed the impact of heavy loads by commodity. In 1998, Louisiana assessed increasing GVW to 100,000 lb. on trucks carrying sugarcane, rice, timber and cotton. The state identified road segments along which each commodity was produced, the number of trucks carrying each load, estimated amount of each commodity hauled, and effect of increasing weight on those road segments over a 20-year period (Roberts and Djakfar 2000). Overall, increasing the GVW decreased the service life of roads. Roads built to carry more ESALs were less affected by increased GVW. Increased GVW subsequently increased the cost of pavement overlays and reduced the time between required overlays.

When analyzing pavement deterioration agencies must distinguish damage attributable to environmental factors from damage caused by the structural impact of vehicles. How vehicle weight is distributed over axles, number of trips made, road design, and other physical and dynamic characteristics (e.g., speed, traffic patterns, tire inflation) must be considered.

2.5 Pavement Design

Roads and pavements are designed for the vehicle traffic demand anticipated throughout their service lives. Factors such as geotechnical assessments of the subgrade, climate, and roadway materials must be considered to ensure the provision of an adequate structure (including base depth and pavement thickness). Pavement thickness and materials differ based on road type and geography. AASHTO's pavement design procedure requires that pavements be designed to carry a certain number of loads over a predetermined period (Barros 1985).

Pavement Types

The three primary pavement types are flexible (asphalt), rigid (concrete), and a composite of the two. Concrete pavements offer greater strength, durability, and skid resistance than asphalt, but construction costs are higher. Flexible asphalt pavements are layered over other materials intended to withstand high stress. For higher traffic levels pavements are laid full-depth directly atop subgrade. The combined strength of all layers is considered in design (Ali et al. 2020). Rigid pavement (i.e., Portland cement concrete [PCC]) is laid atop subgrade or a stabilizing material with no need to account for the combined strength of other layers. Its inflexible material distributes heavy loads over a wider area than flexible pavements.

Roads designed for heavy truck traffic often employ concrete. Concrete pavements are often resurfaced using asphalt, which results in composite pavements with combined characteristics of both flexible and rigid pavements. Overlaying asphalt atop a PCC layer results in a strong base and smooth surface (Ahmed et al. 2014). After initial construction, pavements undergo maintenance and rehabilitation. Different material mixes are used for overlays, patches, and sealants. The design lives of pavement mixes, overlays, and sealants range from 1 to 30 years (Ahmed et al. 2014).

2.6 Pavement Performance and Service Life

Several factors influence pavement service life: traffic, environment, pavement design and materials, vehicle design, and overall road maintenance (Ahn et al. 2011, Li et al. 2012; Qiao et al. 2013; Hajek et al. 1998; Dunning et al. 2016; Ali et al. 2020). Several factors can accelerate damage as loads are increased (Sadeghi and Fathali 2007; Ali et al. 2020):

- Asphalt thickness, composition, age,
- Climate (water content and temperature)
- Subgrade condition
- Number of vehicles travelling, the gross weight and number of axles of those vehicles, whether vehicles are travelling over segments simultaneously (especially in the case of a bridge),
- Speed of traffic and tire inflation

Pais et al. (2013) found that increasing pavement thickness reduced the overall impact of overloaded trucks but designing roads for overload traffic rather than for normal limits increased costs by 100%. Moreover, "it is the traffic (i.e., load intensity, frequency, and axle and tire configuration) that is primarily responsible for pavement problems due to the loads applied by the axles and tires of vehicles. Heavy traffic causes the most important failures in a pavement producing fatigue cracking and rutting that require pavement rehabilitation" (p. 873).

Two vehicle characteristics influence the amount of deterioration caused by heavy trucks: axle configuration and axle load — damage increases exponentially with axle load (Luskin and Walton 2001). In general, adding more weight increases the load magnitude. Axle load concentrations engender different types of pavement distress. When the distance between axles is short, typically on single or tandem axle trucks, heavily concentrated loads increase pavement cracking. Trucks with multiple axles — where loads are spread out over a larger contact surface area — cause more pavement rutting (Salama et al. 2006). Very heavy trucks may impact more than the pavement surface, damaging the subgrade. Dynamic forces resulting from the heavier weight contribute to shorter pavement life-cycles as well. Passive-axle suspension systems and suspension systems with optimized stiffness and dampening minimize pavement damage while heavy trucks exceeding speed limits could decrease service life by 40% (Luskin and Walton 2001).

Pavement Distress from Heavy Trucks

Pavement studies have found rutting is the most common pavement type of distress caused by heavy trucks with multiple axles, although other distresses like fatigue cracking and raveling occur, which may significantly reduce pavement life.

Pavement Damage Measurement Approaches

The two most common methods of evaluating pavement damage and associated costs are the ESAL approach, or *fourth-power law method*, based on AASHTO's 1993 *Pavement Design Guide*, and the Mechanistic-Empirical (ME) method (using fatigue and rutting life) (Ali et al. 2020). The ME approach is primarily used now.

Equivalent Single Axle Approach (ESALs) Approach

The ESAL approach converts axle loads of different truck configurations (single, tandem, tridem) and load magnitudes to a standardized 18 kip. loading. One ESAL represents the pavement damage caused by one pass of an 18,000 lb., single axle with dual-tires inflated to 110 psi. (Ali et al. 2020). The fourth-power law is used as an approximation for ESAL calculation. It states that the damage from a load is approximately the load per axle raised to the fourth power (AASHTO 1993; Abramzon et. al 2014). In the 1960s interstate pavements were designed to accommodate 5-10 million ESALs while many modern pavements are designed to accommodate 50-200 million ESALs (Chowdhury et al. 2013).

Mechanistic Empirical (ME) Approach

The primary difference between pavements designed using an empirical approach and a mechanistic approach is the way traffic is considered (Ali et. Al 2020). AASHTO's *Mechanistic-Empirical Pavement Design Guide* (MEPDG) provides guidance on the ME approach, which models flexible and rigid pavement responses in Pavement Design ME software based on nationally calibrated Long-Term Pavement Performance (LTPP) sections and correlates pavement performance under applied traffic loads (Ali et. al 2020; Saboori et al. 2021). MEPDG modelling requires data on general project information, design criteria, traffic, climate, structure layering, and material properties (including design features). Pavement ME software predicts longitudinal trends in pavement layers, including changes in damage and distress as well as rideability (measured using the International Roughness Index [IRI]).

MEPDG recommends calibrating the software to data on local roads, climate, and materials as necessary. It uses axle load spectra (i.e., distributed axle loads) from bidirectional average annual daily traffic (AADT) and traffic lane data. Damage and distress are predicted by truck configuration (axle load, axle width and spacing, and tire pressure [Ali et al. 2020]).

MEPDG has been used to estimate pavement damage in many contexts. Li and Sinha (2000) used Indiana's PMS data, including IRI, climate, subgrade, design, and pavement ages to estimate the ways in which loads influence pavement and rehabilitation costs. Ong et al. (2010) also used Indiana's PMS data to develop a framework for optimizing pavement preservation treatments and rehabilitation. They created short and long-term pavement performance models and used a service life approach to correlate pavement distress (e.g., IRI, rutting, condition ratings) with AADT and environmental conditions. Batioja-Alvarezet al. (2018) forecasted pavement rutting and fatigue cracking from OW vehicles by accounting for vehicle loading, pavement temperature, and VMT.

Sadeghi et al.'s (2007) evaluation of deterioration patterns in flexible pavements at different loads found that single-axle vehicles produced more pavement fatigue than multi-axle trucks. Salama et al. (2006) compared the impact of different axle and truck configurations on the performance of flexible pavements in Michigan, finding that single and tandem axle vehicles cause more cracking than multi-axle vehicles, whereas multi-axle vehicles led to more rutting. Roughness was not strongly correlated with axle configuration. Gungor et al. (2019) developed a framework to assess damage to Illinois pavements and bridges to update the state's OW/OD permitting fee structure. They developed pavement performance models for asphalt and concrete pavements based on functional class using incremental changes in pavement condition rating surveys (CRS), which they associated with daily ESALs, pavement age, and the freezing index. They extrapolated OW truck traffic from data collected at a few WIM stations in the state's network, ultimately recommending integrating existing online geographic information system (GIS) data at state DOTs to calculate individual fees.

Machine Learning

Studies have typically used regression models to quantify pavement damage from vehicle loads (Zhao et al. 2021), which may not account for all parameters that influence pavement performance. More recent studies have used machine learning methods to predict pavement performance based on ME design data (i.e., axle spectra load and GVW obtained from WIM station data). Gong et al. (2018) used machine learning to predict the IRI of asphalt using measured distress, climate, traffic, maintenance, and structural data. Similarly, Fathi et al. (2019) predicted the alligator cracking index using hybrid machine learning, and Inkoom et al. (2019) predicted pavement cracking based on prior pavement condition ratings. Zhao et al. (2021) described methods for predicting a surface distress index in a given year based on pavement age, average annual ESALs, environmental factors (i.e., freezing index), and model coefficients. They used a support vector regression and machine learning to analyze pavement condition data and truck axle loads to determine pavement damage from OW trucks. Machine learning techniques are powerful predictors and may outperform linear regression models but require large amounts of field data that may not be available in a PMS, such as axle load spectra and GVW (available from WIM data) (Zhao et al. 2021).

2.7 Pavement Damage Cost Estimations

Most states collect revenue to pay for damage caused by heavy trucks. Trucks have typically contributed to road usage fees through higher fuel consumption, gas taxes, registration fees and tire taxes, toll rates per axle grouping, and OW/OD permit fees (Chowdhury et al. 2013). Studies have consistently found road user fees do not adequately cover the cost to repair roads and that heavier vehicles do not pay an equitable portion of the damages (Ahmed et al. 2012; Dey et al. 2014).

Methodologies

It is challenging to value damages and determine how road users should fund their use of roadways. An especially fraught task is determining the level of damage inflicted by heavy trucks carrying commodities important to a state's economy. NCHRP Synthesis 378 (2008) reviews state highway cost allocation studies. Ahmed et al. (2012) reviewed pavement damage cost methods and attribution of damage for road use, or consumption per vehicle type, and their limitations stating that despite decades of research pavement damage cost estimation studies are not consistent.

Studies that estimate the costs of damage typically use a two-step process. First, they assess the magnitude of pavement damage from vehicle loads and then conduct a cost analysis to assign a dollar value to that damage. The assignment of pavement damage costs varies by state due to differences in weight limit regulations, road designs, climate (i.e., moisture and temperature), differences in geotechnical subgrade soil properties, traffic patterns, and other issues. These studies tend to evaluate road sections and treat them as representative of the whole network, which may not be accurate. There is also considerable variability in WIM data.

Cost estimates are highly sensitive. Depending on the method selected, costs may be underestimated by over 80% (Ahmed et al. 2012). Barros et al. (1985) conducted a life-cycle cost analysis on maintenance and repair of New Jersey roads that accommodated OW trucks and those which did not. Estimated pavement costs from damage caused by OW trucks ranged from $7 million to $43 million per year (in 1983 dollars). Net present value was calculated based on initial construction cost, recurring rehabilitation/maintenance costs, rehabilitation/maintenance activity, interest rate, and year in which rehabilitation/maintenance occurs. Other factors that influence costs include:

- Inflation rates
- Average trip length of OW trucks
- Traffic control
- Enforcement costs
- Engineering costs.

Historically, pavement damage costs studies have taken one of two forms: highway cost allocation (HCA) or pavement damage cost (PDC).

Highway cost allocation (HCA)
HCA generally assigns highway repair costs (including highway widening and pavement strengthening projects) to different vehicle classes based on the amount of damage inflicted. There have been several variations of highway cost allocation studies. They look at costs broadly, using the number of axle miles traveled, mileage, ton miles, and ESAL miles and include "vehicle operating cost (VOC), pavement MR&R cost, congestion cost, accident cost, and environmental cost" (Agbelie et al. 2016).

Pavement damage cost (PDC)
PDC estimation studies look at pavement consumption by different vehicle classes and estimate either the full cost of pavement recovery or incremental costs that should be levied on each vehicle class. These studies only examine direct costs to pavements (e.g., maintenance and rehabilitation costs) and exclude costs related to right of way, earthwork, drainage and erosion, other assets (e.g., guardrails), or construction (e.g., additional lanes) (Agbelie et al. 2016).

The cost of damage resulting from heavy trucks is significant. Gibby et al. (1990) showed that heavy trucks with five or more axles had 70 times the impact on pavements as light trucks and were responsible for more than double the costs ($/miles/year) between 1984 to 1987. In Ontario Hajek et al. (1998) showed that pavement damage costs varied considerably by highway type, with new pavements on local roads costing significantly more than freeways ($0.597 vs. $0.0025 in Canadian dollars; a 238.8% difference). In Indiana damage costs ($/ESAL/mile) ranged from $0.0143 to $0.024 for routine maintenance (Li et al. 2002). Agbelie et al. (2016) used an incremental method, including actual highway costs for state and local highways, and allocated costs based on FHWA vehicle classification and VMT. An equity analysis revealed that passenger vehicles overpay for highway consumption while heavy trucks underpay (Classes 5-13).

Life-Cycle Cost Analysis (LCCA)
Today, costs derived from LCCA are used to plan and design new roadway construction. The FHWA report *Life-Cycle Cost Analysis in Pavement Design: In Search of Better Investment* (1998) was instrumental in providing transportation agencies step-by-step guidance on LCCA methods.

Nassif et al. (2015) developed a model for analyzing pavement and bridge deterioration resulting from OW trucks in New Jersey using 10 years of WIM data. Using ME analysis they calculated pavement deterioration costs (PDC) with LCCA and projected highway deterioration over the infrastructure service life. They estimated the average cost of transporting 1 ton of an OW load 1 mile was \$0.33 (with 60% attributed to pavement and 40% to bridges). They recommended a PDC (\$/equivalent single axle load (ESAL)/lane/mile) of "\$0.027 to \$0.052 for interstate and U.S. highways, and approximately \$0.092 to \$0.0483 for state highways" (Nassif et al. 2015).

Leveraging permit data, Nassif et al. 2018 coupled structural and traffic models to conduct LLCA and forecast the economic impact of OW trucks on New York City DOT pavements and bridges along selected corridors. Preliminary estimates of pavement costs per ESAL–lane mile varied from \$0.0345 to \$0.648 (27.6% to 34.2% higher than New Jersey). Data availability limited the study. The authors observed that bridge and pavement inspection reports are needed to model damage and recommended expanding the collection of traffic data beyond select corridors. Ali et al. (2020) calculated pavement damage costs, life-cycle costs, and damage on 37 Florida road segments. Using an ESAL approach they estimated pavement damage (including bridges) at \$0.018 for interstates, \$0.049 for primary arterials, and \$0.147 for minor arterials per ESAL–lane mile.

Pavement Cost Estimation Limitations

Previous attempts at pavement cost estimation studies have been hampered by their reliance on maintenance and rehabilitation costs and neglect of pavement reconstruction costs (Ahmed et al. 2012). Studies grounded in an empirical approach have not adequately addressed the fact that maintenance, rehabilitation, and repair schedules are inconsistent. A road on a 10-year cycle may need more frequent repairs. And repair schedules vary at the statewide level. Studies have also collected traffic data from one or a few WIM locations and generalized data to a broader area, where observed traffic may not be representative of traffic counts or loads (Ahmed et al. 2012).

Chapter 3 Kentucky's Pavements

3.1 KYTC Pavement Design

Kentucky's road inventory includes highways built using asphalt concrete (AC), concrete (PCC), and composites (AC/PC). Although new roads are typically designed with AC, older pavements may be a composite with asphalt over concrete. Subgrades, materials, or pavement thicknesses vary based on differences in geography and climate as well as construction, preservation, and maintenance schedules.

The subgrade over which pavements are laid vary across the state due to soil characteristics. KYTC's *Pavement Design Guide* describes the subgrade of Kentucky's pavements as primarily fine-grained soils; 85% of the state's soils consist of clay and silt.[2] Pavement composition and thickness have changed over time, reflecting updated design standards, construction techniques, materials, traffic counts, and maintenance and rehabilitation (M&R) schedules.

KYTC uses AASHTO's *Guide for Design of Pavement Structures*, MEPDG, and Kentucky's ME pavement design systems. ESAL estimation is no longer used. The Cabinet has adopted a web-based application to the *Pavement Design Guide* which lets designers enter their own criteria into AASHTOWare Pavement ME Design software. The software estimates pavement life-cycle and associated costs for new construction or full-depth reconstruction.

3.2 KYTC Pavement Management

To evaluate the state system's pavement and maintenance performance and budgeting, KYTC's Operations and Pavement Management Branch (PM) collects and analyzes data on pavement, asset conditions, and ride quality. *Pavement Management in Kentucky* (2016) (*The Red Book*) lists the branch's goals as:

- Measure ride quality of all pavements to assess general conditions and estimate current and anticipated improvement needs.
- Perform visual assessments of pavements in order to select and prioritize those in need of rehabilitation or restoration.
- Track and communicate system performance of pavements.
- Assess impacts and recommend changes in programs, practices, policies and specifications affecting condition and performance of pavements.
- Maintain pavement database information for effective communication and coordination of pavement related activities within the Department of Highways.
- Provide data, information, and results of analyses to other KYTC units and outside agencies whenever necessary.

The branch maintains the state's PMS, which includes construction histories for Kentucky's roads, including every non-Rural Secondary (RS) road. Although the data on Kentucky's oldest roads may be lacking integrity due recordkeeping, the PMS provides a good accounting of the layers of materials added and/or changed. Rideability or ride quality scores are not available for RS roads, although appearance scores are kept.

Pavement Condition Evaluations

Prior to 2009, KYTC primarily relied on visual inspections to evaluate pavement conditions. Visual inspections introduce an element of subjectivity and have the potential for reliability issues. Climatic/environmental issues (e.g. sun angle) can affect visibility ratings. Time of year and weather conditions may influence the visibility and severity of some types of distress, so evaluations were conducted around the same time. Evaluations were based on estimates and did not involve manual crack measurements (KYTC 2009).

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[2] Pavements built on recently compacted soil remain strong, but if moisture permeates the soil (i.e., rainwater, snow melt, etc.) swelling reduces the subgrade's bearing capacity potentially producing rutting in the subgrade, weakening the pavement, and consequently shortening lifespan.

Today, a three-vehicle fleet with profilers incorporating Photolog Viewer technology collect data on roadway condition and provide a photographic record with GIS markers. Profilers detect pavement type, markings, and dimensions. They also collect detailed distress measurements, including the longitudinal profile, rutting, faulting, cracking, roughness, raveling, and potholes. Pavement distresses are classified and rated according to type, severity, and extent.

In 2013 KYTC completed an initial inventory of state-maintained roads and began using a parametric laser crack measurement system (LCMS) that automatically detects and measures pavement parameters in a single pass in significantly more detail. From 2009 to 2013 rutting was measured with a 1200-point transverse profile. LCMS measures rutting with a 4000-point transverse profile every two (2) feet. Due to equipment challenges the state did not collect rutting data from 2004 to 2009.

Roadway classification dictates pavement evaluation schedules. At least 98% of all state-owned (MP) sections longer than 0.25 miles and ADT > 375 are evaluated once every three years. Each year at least 98% of interstate and parkway lane miles and NHS roadway miles are tested. Exceptions are made for pavement construction projects or locations inaccessible due to unforeseen circumstances (e.g., flooding). Interstate and parkway ride quality testing are completed by September 30 while pavement condition evaluations are finished by April 30. KYTC reports interstate and NHS pavement conditions and performance to FHWA for the Highway Performance Monitoring System (HMPS) each year. KYTC also contributes to FHWA's Long Term Pavement Performance (LTPP) program, which collects information each year in seven areas: Inventory, Maintenance, Monitoring (Deflection, Distress, and Profile), Rehabilitation, Materials Testing, Traffic, and Climate.

Other state roads are tested on a two-year cycle with at least 45% completed by December 1 each year. Pavement sections are updated in the database by February 15 for milepoint termini, system change, resurfacing date, and traffic, and pavement condition data are distributed by May 15. New construction projects are tested for ride quality within two-weeks of a request.

Historically, the Division of Maintenance in conjunction with the Division of Highway Design prepared a list of recommended, priority-ranked rehabilitation projects along interstate, parkway, and state primary roads in odd-numbered years. The *Six-Year Highway Plan* (SYP) lists recommended pavement treatments and cost estimates for the state system. For the SYP, recommended pavement rehabilitation projects are tabulated by June 30 of odd-numbered years. Tabulations for approved rehabilitation projects are distributed by June 30 of even-numbered years.

KYTC established a preventive maintenance program in 2007, and in 2009 the Operations and Pavement Management Branch began providing districts with a list of sections that would be evaluated during the upcoming season. These sections represent about one-quarter of the MP system and half of the preventive treatments completed in the district. Models from PMS data estimate current pavement conditions. If district staff believe estimates are incorrect, they can add them to the current year evaluation list. KYTC submits condition data from the previous year to districts by March 15. Districts submit resurfacing sections for inclusion on the list by April 15 and preventive maintenance sections by April 30. Evaluations begin in May, with data made available to districts by September 1. By October 31 districts submit windshield cost estimates for resurfacing projects (in the current or upcoming year).

Kentucky Statewide Resurfacing Program (FD05)

FD05 is the funding source for the Statewide Resurfacing Program for preservation treatment administered through the Division of Maintenance. It is limited to MP pavements. Most of KYTC's pavement projects are resurfacing. These are typically done every 10 to 15 years. Pavement conditions usually do not undergo rapid changes however, worsening pavement conditions may warrant a shorter resurfacing cycle. Resurfacing projects are constrained by budget limitations.

Pavements on the MP system are evaluated on a three-year cycle. Recommendations for resurfacing are based on several factors, including the engineer's assessment of overall condition, rate of deterioration, and traffic loads (KYTC 2016). Pavements are grouped by recommended year of resurfacing and ranked by condition. Districts may add up to five distress points on pavement sections to elevate their ranking and modify the recommended treatment year to avoid conflicts with other projects. An effort is underway to revisit pavement resurfacing prioritization using the Analytic Hierarchy Process (AHP).

3.3 Pavement Distress Types

The Red Book (2016) describes types of pavement distress and evaluation criteria for Kentucky. Some distress measures used in this study (e.g., pavement distress index (PDI)) are not reviewed in the publication. FHWA's *Distress Identification Manual for the Long-Term Pavement Performance Program* (2014) serves as a pavement distress dictionary that defines distress types and explains measurement techniques for AC surfaces, jointed PCC, and continuously reinforced concrete. KYTC's pavement condition evaluations document the severity and extent of each distress type. Pavements are ranked on a demerit point system — more demerit points indicates worse pavement damage. Several indices are used to evaluate pavement condition quality: the Present Serviceability Index (PSI), Pavement Condition Index (PCI), IRI, and PDI.

International Roughness Index (IRI)

The IRI measures pavement roughness (i.e., smoothness or ride quality). FHWA requires IRI reporting for 0.10-mile intervals or greater (per 24 C.F.R § 490.309). Longitudinal profile measurements from the left and right wheel paths of a model vehicle are averaged for IRI values. The IRI has limitations. Traditional initial profilers (height sensor, accelerometer, and distance measuring instruments) have problems with low speed and when stopped (TRB 2022). For example, travelling slower speeds increases smoothness (resulting in better IRI). Stops may show up as roughness when they might not be. Road roughness does not provide a comprehensive picture of pavement damage and necessary maintenance or rehabilitation.

Pavement Distress Index (PDI)

Grivas et al. (1990) established methods for determining the PDI which uses information from individual distress ratings and weighted averages for distress types and severity from individual pavement sections. The methods have changed over time with the addition of new distress calculations. PDI accounts for all types of distress, not specific types of distress individually: transverse cracking, raveling, wheel path cracking, IRI, appearance, joint separation. Depending on study objectives the PM Branch may sometimes use only WPC Extent and WPC Severity, along with Joint Separation to look at pavement condition. PDI values range from 0.00 – 1.00, with higher values indicating more distress. In Kentucky PDI values are calculated at 0.10-mile intervals. The PM Branch generally recommends resurfacing at PDI values of 0.5 – 0.55. Values greater than 0.56 are a sign of poor pavement.

Chapter 4 Kentucky's Pavements Condition Study

4.1 Methodology

Kentucky Transportation Center (KTC) researchers developed regression models to compare pavement performance on the EWCHRS and primary state highway system. The PDI was used to quantify relative changes in pavement surface conditions for similar roads on both systems between 2008 and 2020. Researchers also accounted for maintenance scheduling and whether truck traffic increased the need for maintenance faster. Data from the EWCHRS and primary system were matched based on PDI analysis year and AADT. PDI analysis year was aligned with overlapping EWCHRS segment years since many EWCHRS segments were discontinuous (i.e., they came on and off of the system). The primary state highway system included many more miles than the EWCHRS. Data were not matched for truck configuration nor geography.

4.2 Data Sets

ECHRS Data

KYTC's Division of Planning maintains data for reported coal and coal-byproduct tonnage on Kentucky's roads and designates the annual EWCHRS officially ordered by the Secretary of Transportation. The division provided KTC researchers with official EWCHRS documentation for 2008 – 2020 (2016 was unavailable).

Pavement Condition, Construction History, and Resurfacing Data

KTC researchers obtained data from the PM Branch on rutting, visual distress, PDI, IRI, out of section, fatigue (base failure), and cracking for EW sections and the state primary system. Data sets used in analysis included:

- INPK (2008-2020): Data on Interstates and Parkways
- IRI (2008-2019): international roughness index (from PMS_HPMS_DATA_LCMS)
- IRI (2008-2014): from Ride survey table (IRI_RUT_PMS_Ride_rutsurvey.sql)
- RUT (2015-2019): Rutting (from PMS_HPMS_DATA_LCMS)
- Rutting (2009-2014): from Ride survey table (IRI_RUT_PMS_Ride_rutsurvey.sql)
- FD05 (2016-2020): resurfacing data with construction history

FD05 Condition Data

After reviewing data with the PM Branch, researchers analyzed FD05 resurfacing data tied to construction history. The FD05 database includes county and route numbers, cardinal lane directions, year of evaluation, bidirectional AADT, recommended treatment years, and PDI. Rutting data are not included. Pavement types analyzed included AC overlays, AC construction, and a several other categories.

Construction History

The construction history field indicates the year of construction or treatment, beginning and ending milepoints, treatment type, and thickness of pavement layers. These are not separate fields broken apart into component parts. KTC researchers used an SQL query to retrieve the most recent treatment layer, but KYTC had not yet separated the field programmatically.

Pavement Distress Index (PDI)

The PM Branch began collecting PDI data around 2016 for state primary, secondary, and supplemental routes, but not RS routes. PDI data are not available for the earliest years of the EWCHRS. Studies of pavement condition and the EWCHRS have used other distress data (i.e., IRI). This study accounts for distress types not previously evaluated. Theoretically, the PDI data used in this study could evaluate a pavement in 2016 that was 12 years old (predating the data for which EWCHRS data were available). As PDI can also be aligned with pavement costs, PDI was thought to provide the most reliable results.

PDI is evaluated approximately every three (3) years. The interval between assessments may be shortened due to excessive deterioration or extended in some circumstances (e.g., resurfacing is done). Some pavements have PDI values for 4–5 years. This example shows the importance of aligning PDI values with construction history. Because routes have resurfacing while others do not during that three-year period, there are some overlaps between PDI and construction history data that required reconciliation.

Surface Data Limitations

An average of each distress does not provide a clear picture of the magnitude of damage, especially for short periods. Surface data do not tell the whole story of how heavy trucks impact pavement. They only capture distress types — not base failure. Base failure analysis requires analysis of pavement subgrade samples. Nonetheless, averaging distress data collected at 0.10-mile intervals on the EWCHRS and primary system indicates whether more distress occurs on the EWCHRS.

The analysis did not consider RS routes (they are excluded from pavement condition assessments) or interstates and parkways. EW vehicles cannot travel on interstates, and parkways do not always carry EW loads. Parkways are also designed to carry higher AADT and heavy truck traffic.

Comparing parkways would require analysis of the actual weight on the roads. This would include EWCHRS tonnage data, AADTT (number of trucks on the roads), and ideally measures of the actual weights of both EW trucks and non-permitted legal trucks. KTC researchers assumed that if EW decaled trucks had a greater impact on pavements than the state primary system damage would likely appear on lower-class routes not designed for higher AADT. Analysis began with lower-class routes assuming heavy loads would have most impact and roads would exhibit the most distress. Older, lower-class routes are less likely to have undergone geometric design and are more likely to have evolved from preexisting dirt roads.

AADT

KTC researchers derived AADT values from the Division of Planning's traffic count data. A positive correlation exists between AADT and the likelihood that a road was geometrically designed. While the FD05 database includes bidirectional AADT, the EWCHRS does not distinguish direction. Kentucky requires that EWCHRS trucks be registered, and decaled trucks are not permitted to operate above the registered GVW. The Department of Motor Vehicles maintains data on EWCHRS permits, however, the number of trips per vehicle is not reported. The researchers cannot determine from AADT the number or percentage that are EWCHRS decal trucks. Nor can they know precisely how much weight is carried on state roads. Kentucky’s WIM stations are primarily located on interstates and major US highways. EW trucks are prohibited on interstates, and continuous WIM monitoring data do not exist. It is possible there are more non-EW trucks on the EWCHRS than the base system. Trip lengths for vehicles hauling coal are assumed to be very short. Segment lengths of the EWCHRS ranged from 0.004 to 61.119 miles. The shortest was CR 1163 in Lawrence County in 2009 (0.000 to 0.004) and longest was KY 194 in Pike County in 2009 (11.7 to 72.819).

4.3 Data Analysis

Data analysis proceeded in four steps:

1. Data cleaning: conversion of EW PDF files to electronic format
2. Quantification of exposure on the EW system
3. Analysis of impacts on pavement life
4. Cost analysis for impacted resurfacing

Data Cleaning

EWCHRS data received as PDFs were converted to an electronic format.[3]

[3] Electronic format was not available from KYTC’s Division of Planning and data were later obtained from KTC’s HMPS database.

Quantification of Exposure to the EW System

KTC researchers determined the length of time road segments were part of the EWCHRS. To quantify the amount of time roadway segments were on the EWCHRS we calculated the metric *Percent EW Exposure* — the measure of length and time a pavement section was part of the EW system during study period. This established a baseline age for each surface on the EWCHRS. Reconstruction on a segment reset the exposure period to zero. *Percent EW Exposure* was calculated using the following steps:

1. Overlapping Milepoints of EWCHRS Exposure and PDI Evaluation
2. Total EW miles
3. Possible EW Miles Per Year
4. Total Percent Exposure

Overlapping Mileage

KYTC's construction histories do not perfectly align with PMS condition data for PDI. Occasionally, pavement evaluation segments were extended or shortened to better align pavements with similar conditions or when these changes provided a more logical termini for construction. When these changes are made, the resulting segment may have different construction histories and thus different surface ages. To categorize pavement evaluation segments by age, each segment was evaluated to determine the level of consistency for its surface age. As long as 75% of a segment had a consistent age we used the corresponding PDI value for the entire segment. For example, if 75% or more of a pavement segment was 10 years old, the entire segment was assigned an age of 10 years. Conversely, if at least 75% of the segment did not have a consistent age, PDI data were excluded. This process potentially introduces error into the analysis.

A very small percentage of total sections had overlapping condition data. For example, one evaluation section might end at milepoint 3.0 and the next might begin at 2.9 — creating an overlap from 2.9 to 3.0. This may occur if an adjustment were made to one section but overlooked in the adjacent section. There were 382 such instances, which could potentially be 191 pairs, but in some cases more than two sections overlapped, so the total number of physical sections impacted could be less than 191. KTC researchers used the following rules to handle these cases:

1. Adjusting termini for one section or the other if the overlap was less than 0.1 mile
2. Eliminating any record that was not consistent with adjacent records
3. Averaging the PDI values if 1 or 2 were not feasible.

After expunging redundant condition data, PDI value(s) (for the OFFSET_FROM and OFFSET_TO milepoints) were obtained for each construction history record pulled from PMS. The two PDI values were often the same because evaluations of sections generally align with the construction histories. If the values were not the same, they were averaged. If there was only one PDI value, that value was used.

Total EW Miles

Because PDI evaluations are typically done on a two-year cycle, for some years the PM Branch did not have data for when EW trucks were on the EWCHRS. *Total EW Miles* is the sum of the number of overlapping miles segments on the EWCHRS from 2008 to 2020 for which PDI data were available.

Possible EW Miles per Year

Possible EW Miles per Year is calculated by multiplying the number of years in the sample (12) by the length of the EWCHRS segment (beginning and ending mile points).

Percent EWCHRS Exposure

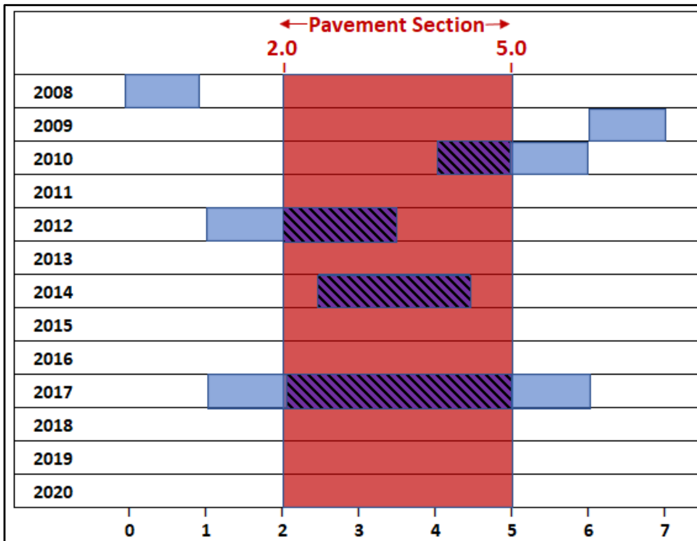
Percent EWCHRS Exposure (EW%) is calculated as follows:

$$EW\% = Total\ EW\ Miles / Possible\ EW\ Miles$$

Example of Data Overlap

Figure 4.1 illustrates different ways in which pavements sections can overlap on the EWCHRS. The pavement section (shown in red) begins at milepoint 2.0 and extends to milepoint 5.0. The EWCHRS (indicated in blue) overlapped this pavement section in 2010, 2012, 2014, and 2017. Where the EW system overlapped the pavement section is shown in purple.

For each year with overlapping milepoints, the number of EW miles for the section was recorded. EW miles for all years were summed to determine *Total EW Miles*. In this example, *Total EW Miles* is 7.5. *Possible EW Miles* was calculated by multiplying section length (3.0 miles) by the number of years (12). Due to missing 2016 EWCHRS data, the number of years of Possible EW Miles calculated is 12. This results in 36.0 *Total Possible EW Miles*. Dividing *Total EW Miles* by *Possible EW Miles* returns an EW% of 19.2%.



Year	EW Section Milepoints	Overlapping Miles	EW Miles
2008	0.0 to 1.0	None	0.0
2009	6.0 to 7.0	None	0.0
2010	4.0 to 6.0	5.0 - 4.0	1.0
2011	None	None	0.0
2012	1.0 to 3.5	3.5 - 2.0	1.5
2013	None	None	0.0
2014	2.5 to 4.5	4.5 - 2.5	2.0
2015	None	None	0.0
2016	None	None	0.0
2017	1.0 to 6.0	5.0 - 2.0	3.0
2018	None	None	0.0
2019	None	None	0.0
2020	None	None	0.0
		Total	**7.5**

Figure 4.1 Example EWCHRS and PDI Evaluation Overlap (2008 – 2020)

AADT

PDI values for EWCHRS segments categorized by age were plotted against roadway AADT. AADT from 0 to 10,000 and 0 to 20,000 were used to evaluate PDI for lower-class roads with EWCHRS trucks and normal operating traffic on the primary system. Table 4.1 lists the number of roadway segments the PM Branch evaluated between 2016 and 2020 on the EWCHRS at all AADTs:

Table 4.1 Roadway Segments Evaluated by KYTC (2016 – 2020)

Percentage of Time on the EWCHRS for all AADT	Number of Roadway Segments with PDI Evaluations
10-100%	516
20-100%	391
50-100%	218
75-100%	118
100%	27

Of the road segments with PDI data, 27 remained on the EWCHRS during all 12 years. There were 516 road segments on the EWCHRS between 10% and 100% of that time. The shortest segment on the EWCHRS with a PDI evaluation was 1/8 mile. The longest segment was 11.7 miles.

Regression Analysis

KTC researchers used regression modeling to examine the relationship between PDI and age on the base system and EWCHRS routes. The inverse log predicted the age at which the lines crossed the target PDI 0.5 and 0.55 values to calculate lost pavement life. The age at Target PDI for both EW and the base system were obtained. EW age was subtracted by the base system, resulting in lost pavement service life. There were not enough data points to analyze primary and secondary routes separately (and keep a valid r-squared value).

Chapter 5 Results

Findings

Routes that spent at least 20% of the study period on the EWCHRS saw a reduction in pavement life of 1.4 – 2 years. KTC researchers assumed that routes on the EWCHRS for longer periods would show more pavement degradation. The results predict the minimal length of time a section needs to spend of the EWCHRS for distress and loss of pavement life occur. While the trend line (Figure 5.1) suggests that pavement distress on segments which spend more than 12 years as part of the EWCHRS should worsen, field data showed improvement. Several possible explanations account for this paradox:

- Older PDI values were the product of subjective evaluations and may reflect human error.
- Not as many roads have been on the EWCHRS for extended periods, therefore fewer data points are available for comparison.
- Pavements are typically resurfaced every 12 to 15 years, so construction histories may be wrong.
- Patching is typically done in 1/4 mile segments and thus is not recorded. Over time as more segments are patched the road condition improves. Due to greater data variability for construction history after 12 years, the PM Branch only looks at 12 years of data.
- Poor conditions on some sections could result from base or substructure damage, which are tackled after about year 9.

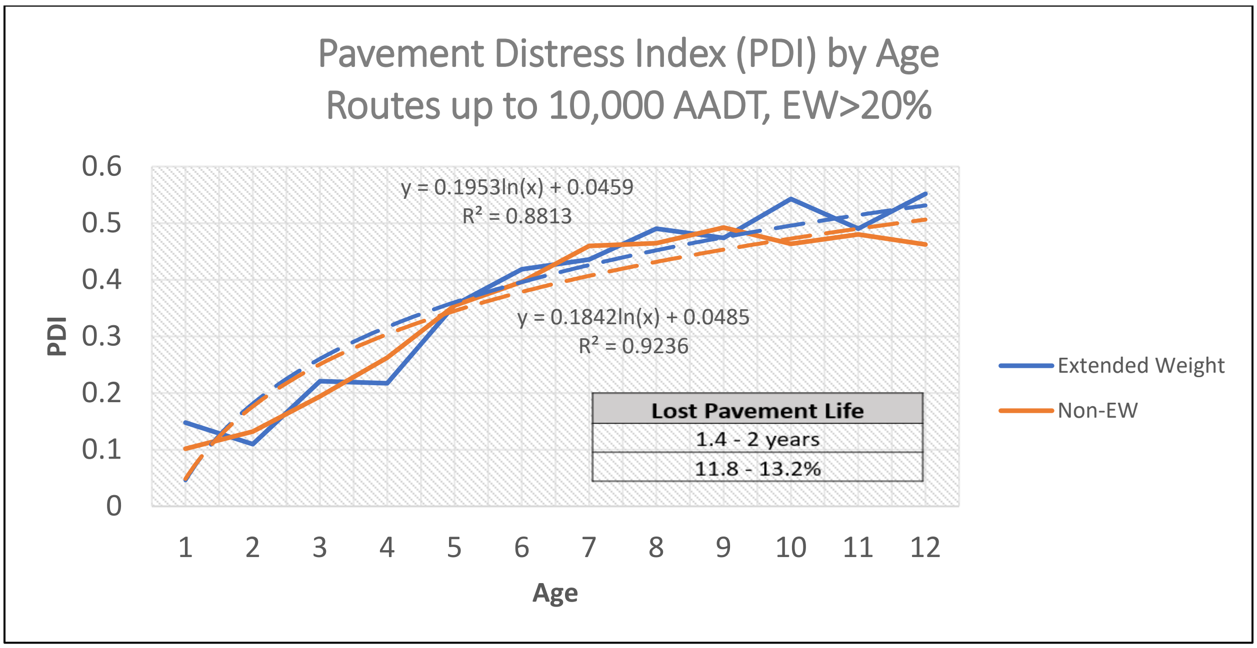


Figure 5.1 Pavement Distress Index (PDI) by Age (Routes up to 10,000 AADT, EW>20%)

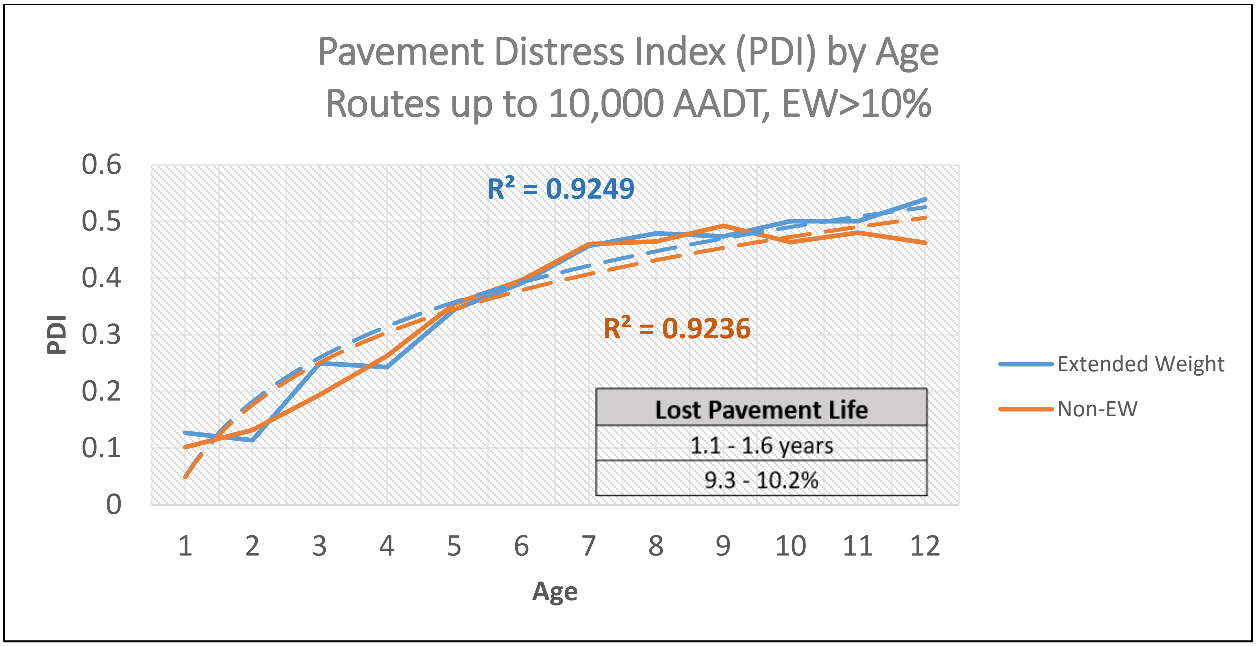


Figure 5.2 Pavement Distress Index (PDI) by Age (Routes up to 10,000 AADT, EW>10%)

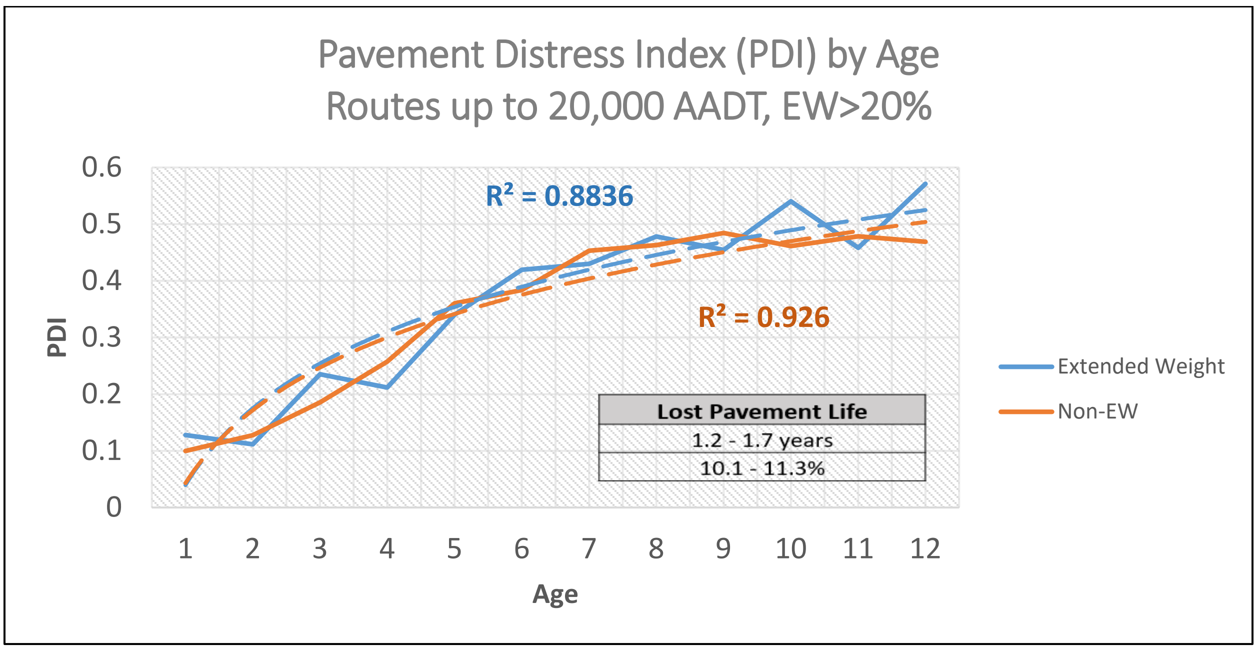


Figure 5.3 Pavement Distress Index (PDI) by Age (Routes up to 20,000 AADT, EW>20%)

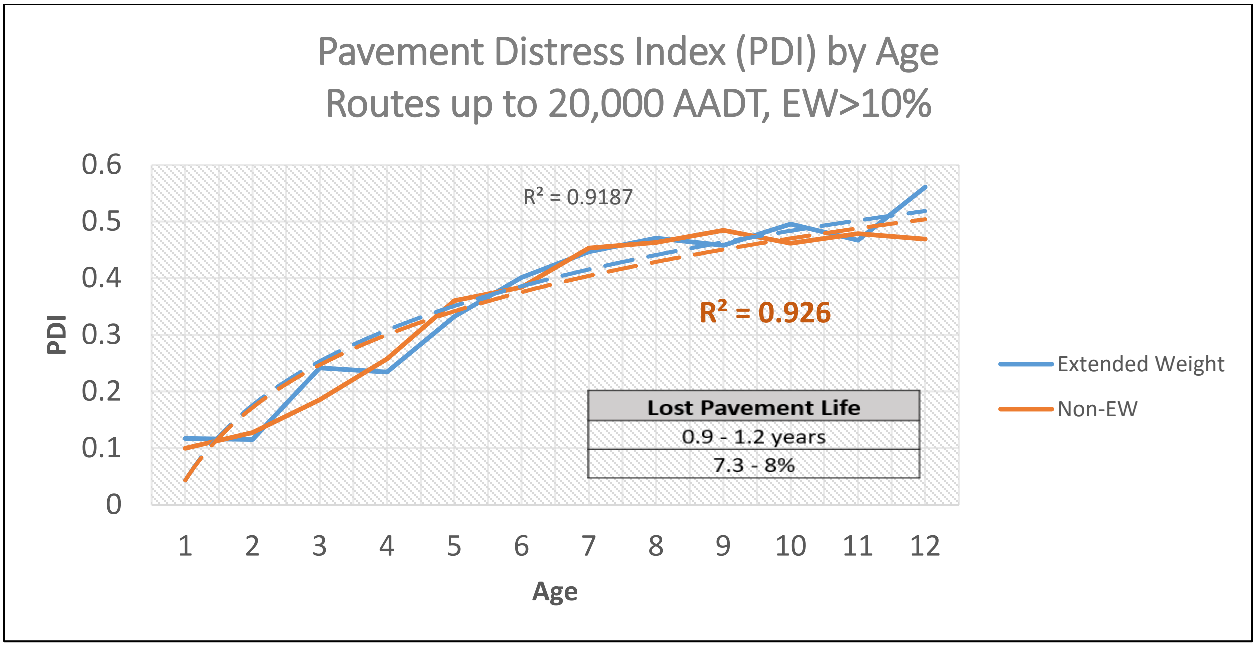


Figure 5.4 Pavement Distress Index (PDI) by Age (Routes up to 20,000 AADT, EW>10%)

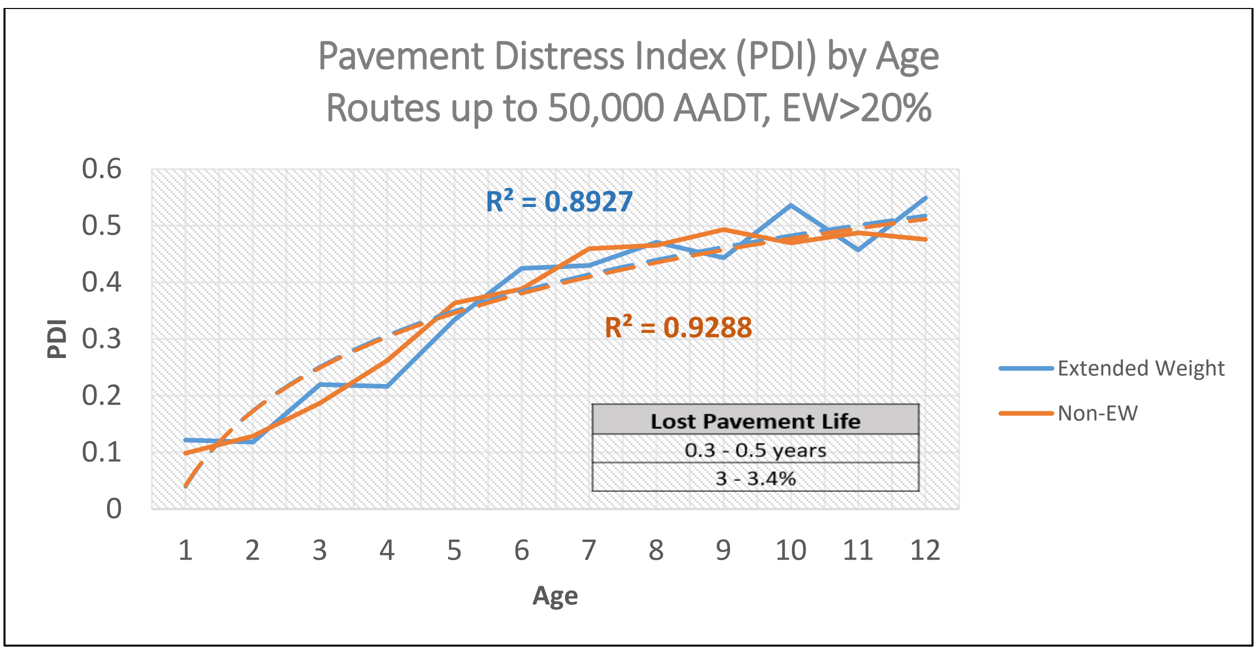


Figure 5.5 Pavement Distress Index (PDI) by Age (Routes up to 50,000 AADT, EW>20%)

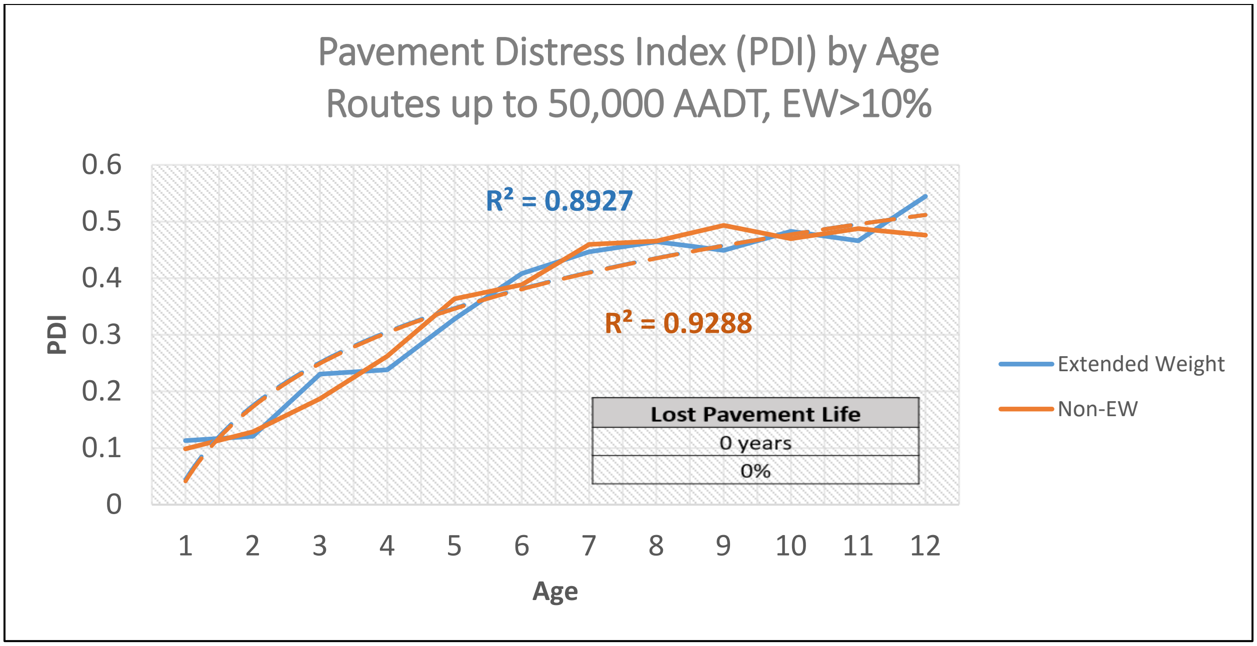


Figure 5.6 Pavement Distress Index (PDI) by Age (Routes up to 50,000 AADT, EW>10%)

Table 5.1 Lost Pavement Life in Relation to AADT and Percent EW Exposure

AADT (Up To)	EW Exposure	Lost Pavement Life	
		Years	%
10k	>10%	1.1 - 1.6	9.3 - 10.2
10k	>20%	1.4 - 2.0	11.8 - 13.2
20k	>10%	0.9 - 1.2	7.3 - 8.0
20k	>20%	1.2 - 1.7	10.1 - 11.3
50k	>10%	0.0 - 0.0	0.0 - 0.0
50k	>20%	0.3 - 0.5	3.0 - 3.4

Cost Impacts

Discerning the precise monetary impacts to the pavement system caused by the influence of the EW system is difficult because location data associated with certain pavement expenses are unavailable. Maintenance costs for activities associated with pothole patching, base failure repairs, and contract paver patching are not consistently available for all districts throughout the study period. Without these data present it is challenging to gauge total costs incurred within the EW system.

PDI data provide a method for describing minimum costs associated with more frequent resurfacing of EW system routes. The regression model predicts 11.8% to 13.2% lost pavement life for pavement segments with AADT values up to 10,000 and EW Exposure greater than 20%. Knowing this, KTC researchers analyzed the EW network to identify the total lane mileage of state roads that meet these criteria. Several route types were excluded: interstates, parkways, county road, and city streets. Two-hundred seventy-four (274) roadway segments met these AADT and Percent EW Exposure criteria. Their total length was 1,556.3 miles (3,548.6 lane-miles). Data from the PM Branch indicate the average cost of resurfacing a lane mile is $75,000, which suggests it would cost $266.1 million to resurface these segments.

The average expected life of non-EW pavements with AADT values of less than 10,000 was 11.6 years before PDI values reached 0.50 and 15.2 years for PDI values of 0.55. If pavements with similar AADT values and an EW% greater than 20% deteriorated at the same rate as those with no EW exposure, annual resurfacing costs for those pavements would be between $17.5M and $22.9 million. Using the more rapid resurfacing cycles of 10.2 – 13.2 years found in pavements with EW% greater than 20% yields annual costs of \$20.2 million – \$26.1 million. Subtracting the difference in these values indicates an increased annual cost of \$2.7 million – \$3.1 million.

Study Limitations
Issues with data availability resulted in several limitations:

- Analysis was restricted by available EWCHRS and traffic count data from the Division of Planning, pavements evaluated by the PM Branch, and resurfacing history.
- KYTC had no EWCHRS data for 2016. Approximately 1/13 of the annual data on EW Exposure are missing, resulting in a maximum impact of 7.7% on the EW% for that year.

The study analyzed PDI values as the cumulative effect of surface pavement damage on the EWCHRS and state base system. KTC researchers did not assess individual points of distress, roughness, or potential pavement damages that may result from heavy trucks. To understand the full effect of pavement damage from EW trucks driving on the centerline requires field data on pavement subgrade. Subgrades vary by location, and newer routes have different bases than older routes. Newer roads typically receive 6 inches, while 8 inches was used on older routes. There could be a 14-foot road with a 3-inch base allowing EW because trucks in the previous year carried 50,000 tons of coal. These could be A or AA roads.

The study did not consider routine maintenance (e.g., patching) — data on these activities are not typically maintained for 1/10 mile increments. Nor did researchers look at other potential sources of damages or costs (e.g., shoulders, guardrails strikes, bridges, ramps, crashes, administrative expenses). With many different treatments used on roads, costs vary. Data were not lane specific and, for certain sections, not rehab specific. The Operations Management System (OMS) tracks maintenance spending but not at the route level, preventing analysis of EWCHRS segments. The database only includes state-level funding, not contracted work. OMS data lack reliability due to inconsistent and incomplete field reporting, although the system has tremendous potential. The data do not provide detail at the 1/10 mile increments on maintenance, rehabilitation, or resurfacing expenses. Instead costs are allocated to an entire project, even when one small section may have accounted for most of the expenses. A new mobile OMS version (as of June 2022) should improve data collection in the field.

KYTC does not have distress data for lower AADT RS routes. Historically, these roads were not typically designed. KTC researchers assumed there are fewer EWCHRS trucks on these routes, but vehicles cause more damage than on primary routes because the pavements were not designed to carry heavy trucks. The analysis looked at cumulative AADTs only and did not account for actual weight on the roads. Results indicated minimal change in lost pavement life if the Percent EW Exposure is 20% or 50% but data reliability declines with fewer data points. Higher-AADT routes are more likely to be designed to carry more traffic. Yet, the percentage of EW trucks is probably less on higher-AADT routes. Since there is a difference between EWCHRS and the base system, EW routes may last longer than base routes on higher-AADT roads. These may have more robust pavements, or they may be resurfaced more frequently.

KTC researchers did not calculate annual resurfacing costs attributable to lost pavement life. Resurfacing costs alone do not accurately capture all the costs of pavement damages caused by EW vehicles, including substructure damages or other maintenance. It does not factor in increased costs for more robust pavement designs for higher-AADT roads. Designing pavements that can support EWCHRS loads is more expensive due to different asphalt mixtures and/or thicknesses.

Chapter 6 Summary of Action Items and Future Considerations

Using EWs for hauling coal increases transport efficiency, but transporting the same loads in more trucks with less weight would employ more drivers, register more vehicles, and very likely cause less damage to infrastructure and reduce maintenance costs. As coal production continues its decline, Kentucky will look to other markets to drive its economy. The General Assembly will need to determine if there is an economic justification for commodity-based EW networks. KYTC can strengthen its ability to support of EW networks through improved data management systems. Strategies for achieving this goal include the following:

- Maintenance data for pavements and bridges need to be available in a form so that costs can be allocated based on vehicle consumption.
- The PM Branch retains surface distress data, but comparing one road to another requires looking beneath the surface. Utilizing more comprehensive structural testing will let KYTC staff examine pavement thickness design loads in greater detail.
- Maintain an electronic database that stores Coal Haul Highway System data
    - The Division of Planning only keeps PDF records of annual EWCHRS data, which hinders data analysis. Electronic documentation will streamline administrative requests and facilitate analysis.
- Expand WIM data collection to EW routes and include truck configurations in AADT
    - Kentucky lacks true AADTT and WIM counts. KYTC cannot document how many trips EW trucks make each day, on which routes, or their weights. The EW petroleum system requires GPS in permitted trucks to map their routes, but this is not required for EW coal trucks.
- There is some ambiguity about when transportation plans need to be filed to ensure districts report damage on roads near mines before KYTC performs engineering analysis. Extensive damage may occur six months prior to KYTC notification. Coal trucks may transport coal on RS routes for a short period (e.g., 6 months) then cease operations. If the cumulative weight of those trucks is less than 50,000 tons annually, the route is not placed on the EWCHRS, despite a significant amount of weight having been transported, including on ramps.

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