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Article

Physical Impacts of 2020 Labor Day Wildfires to Oregon Highways

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Abstract: Wildfires can be destructive to highway infrastructure. Despite the substantial number of wildfires experienced every year, research on the physical impacts of wildfire on highways has been understudied. This research examines historical and potential future highway physical damage from wildfires. To accomplish our research objectives, we examined three major areas related to physical harm to highways and the consequences of that damage – physical characteristics, roadway impacts, and traffic impacts. These categories were subsequently broken into additional metrics, the first being physical characteristics, which includes length of highway affected and reduced average daily traffic (RADT) impacts during the event. Roadway impacts were broken into the number of trees requiring removal (those that present a danger either standing or fallen), pavement damage (burning asphalt concrete), slope/rock scaling (loose hazard rocks/vegetation), and structural damage (guardrail, signs, and delineators). Traffic impacts included the need for traffic control, road closures required, and reduced annual average daily traffic (RAADT) impacts for the year. The physical characteristics on the three highways researched during the 2020 Oregon Labor Day wildfires (Beachie Creek, Archie Creek, and Holiday Farm) indicated less than 61% of the highways were affected. The highway impacts, which included damage from hazard trees, damage to various structures – guardrail, signs, and delineators as well as bridges, slope/rock scaling damage and pavement destruction – averaged 34% for the three highways, while the three of eight arterial highway routes studied in the Oregon Cascades saw a 21% reduction in AADT. Results from this study can be used not only to assess physical damage to highways from wildfires, but as a baseline for measuring and assessing potential future wildfire highway impacts.

Keywords: wildfire; roadway; infrastructure damage; risk; hazard; Oregon 2020 Labor Day wildfires; transportation vulnerability

INTRODUCTION

Wildfire is an unplanned ignition occurring in forested and non-forested landscapes (Mostafiz et al., 2022). Approximately 84% of wildfires are started by humans or human infrastructure but include lightning ignitions as well (Balch et al., 2017) and are a major natural hazard globally, representing the third most costly natural hazard in the U.S., following hurricane/tropical storms and flooding (Escaleras et al., 2022). Despite U.S. spending exceeding \$3.7 billion yearly on fire suppression, wildfires destroyed more than 35,000 properties in 2017 and 2018, resulting in losses of \$32 billion in property and more than 100 fatalities in the U.S. (French, 2021).

Highways play a crucial role in the economic growth of a nation. By lowering travel times and expenses and increasing a region's economic appeal, the creation of a high-quality road network directly boosts a country's economic production. Understanding the value of domestic infrastructure

investment and comparing it to the significant expenses of constructing and maintaining domestic roads is crucial for comparing it to the relationship between domestic transportation networks, market integration, and globalization (Rogers & Enright, 2023). Economic conditions are improved by connecting geographically isolated populations through transportation (Kitchens et al., 2020). The accessibility of the region's transportation infrastructure affects both company and individual economic activity. Furthermore, a population's economic situation can be improved by having a strong transportation infrastructure (Sobieralski, 2021). Companies can reduce transportation expenses thanks to an effective and reliable transportation infrastructure, which also lowers production costs and boosts productivity and profits (Keane, 1996). The importance of highways becomes especially pronounced when considering the destructive potential of wildfires. The destruction wildfires cause to highways can harm local economies by destroying timber, deterring recreation and tourism, and reducing agricultural output, among other things. Replacement of lost facilities and related infrastructure, reduction of watershed and water quality impacts, and restoration of vulnerable species and habitat are all factors that have a long-term impact on state and local budgets (Diaz, 2012).

Unfortunately, little research has been conducted on how wildfire impacts highways, despite infrastructure damage being a significant part of overall wildfire destruction (Habermann & Hedel, 2018). The overall objective of this research is to quantify the damage to highway infrastructure from wildfire by assessing the physical consequences of wildfire damage and therefore improving risk assessments and planning efforts that mitigate negative outcomes. We focus on three elements of wildfire-caused highway impairment – physical characteristics, roadway impacts, and traffic impacts. The following metrics were then separated out from these categories: Physical criteria included the length of the impacted highway and the impacts on the average daily traffic (ADT) during the event. The following groups were used to categorize the impacts on roads: the quantity of trees that needed to be removed (those that presented a danger, either standing or fallen), pavement damage (burning asphalt concrete), slope and rock scaling (loose hazard rocks and vegetation), and structure damage (guardrail, signage, and delineators). In terms of traffic impacts, there were requirements for traffic control, required road closures, and annual average daily traffic (AADT) counts.

The U.S. state of Oregon has historically been impacted by megafires (i.e., fires exceeding 40,000 ha), often driven by synoptic weather events that include high winds and low relative humidity. Since 1900, several significant fires have occurred across western Oregon, including the Yacolt Fire in 1902, the Bandon Fire in 1936, the four Tillamook Burns in 1933, 1939, 1945, and 1951, the Silver Complex Fire in 1987, the Biscuit Fire in 2002, the Chetco Bar Fire in 2017, and the Eagle Creek Fire in 2018. These fires collectively consumed 981,363 ha. (Mass et al., 2021). 2020 was the warmest meteorological summer in the Northern Hemisphere and the second driest year on record for the western U.S. The result: five megafires in western Oregon developed over the 2020 Labor Day weekend (Evers et al., 2022). The 2020 Labor Day wildfires burned more land in the Oregon Cascades than had burned in the previous 36 years combined and, in all probability, exceeded the area burned in any single year for the past 120 years (Abatzoglou et al., 2021). By analyzing the physical effects on three highways in Oregon during the 2020 Labor Day wildfires, a baseline may be established for calculating the risk of wildfire damage to highways.

This research provides a framework for generating standardized formulas to measure highway damage, and in turn, predict potential future damage from wildfire events. Our analysis using data from visual inspections facilitates consistent ways to measure damage based on fire size and roadway length, assisting local, state, and federal agencies in making decisions regarding mitigation of damage to critical infrastructure.

BACKGROUND

A global issue, wildland-urban interface (WUI) – where development meets wildland vegetation (Radeloff et al., 2005; Maranghides & Mell, 2011) – fires are becoming more significant over time as a result of climate change and increased urbanization in WUI locations (Intini et al.,

2019). The density of fires and associated risks has increased in the last 20 years due to the growth of urban and WUI areas, and more focus is being placed on the WUI, which is the region where people are most at risk from wildfires because of the close proximity of flammable vegetation (Nunes et. al., 2023; Radeloff et. al., 2018; Bento-Gonçalves & Vieira, 2020; Fox et. al., 2014). Based on 125 million unique building sites, researchers produced new WUI maps for the United States that provide greater spatial resolution than those produced before using data from the U.S. Census on housing, while maintaining the original Federal Register definition of the WUI represented by WUI maps based on the 500-m neighborhood, which do not include remote, solitary buildings, but rather groups of buildings in and near wildlands (Carlson et al., 2022). Using both WUI and non-WUI land-use categories, the building loss in WUI catastrophes was evaluated in relation to the census-based and point-based WUI maps, while comparing the building losses in connection to the key elements of the United States Federal Register definition of WUI, including dwelling density, plant cover, and proximity to significant areas of wildland vegetation (Caggiano et al., 2020). Recent studies reviewed the key ideas concerning the WUI's intrinsic characteristics and wildfires in the WUI, the evaluation of methodologies that have been used to the WUI, and to analyze several risk prevention and reduction initiatives created in WUI affected by forest fires around the world (Bento-Gonçalves & Vieira, 2020).

Post-fire debris flows pose a major threat to infrastructure, particularly roadways (Fraser et al., 2020). A better quantification of debris flow risk and more efficient debris flow mitigation have been made possible over the past 30 years by technological advancements in mapping fire effects, improvements in our scientific understanding of post-fire debris flow occurrence, and the development of empirical models to predict debris flow probability and volume (De Graff, 2014). These debris flows appear to be independent of the vegetation community burned and are primarily produced by the process of increasing entrainment of material eroded off hillslopes and channels by surface runoff (De Graff, 2018). In southeast Santa Barbara County and southwest Ventura County of California, 281,893 acres (114,078 ha) of land were destroyed by the Thomas Fire between 2017 and 2018 (Swanson et. al., 2022). On January 9, 2018, an atmospheric river storm passed across the area, causing post-fire debris flows and heavy rains in the burned area's western and northern regions (Swanson et. al., 2022). The town of Montecito was submerged by the most lethal and destructive flows, resulting in 23 fatalities (Swanson et. al., 2022).

In addition to debris flows, wildfires also impact steep mountain slopes, potentially increasing rockfall activity. This is due to the removal of organic matter from the soil matrix, such as decayed wood and plants, as well as an increase in erosional processes such dry ravel (De Graff et. al., 2015). The dangers to vehicles posed by the challenge of identifying the road segments that will be affected, the size, number, and/or travel behavior of rocks that may impact a given road segment, and the challenge of predicting how long increased rockfall activity may last after a wildfire (De Graff et al., 2015) have been the subject of additional rockfall activity research (De Graff & Gallegos, 2012). New detachment areas and a prolonged rockfall-runout are also observed following a wildfire (Sarro et al., 2021). Furthermore, areas lacking a history of burning are now suffering from forest fires, which can raise the risks of dangerous mudslides that are exceedingly difficult to forecast (Palmer, 2022).

The relationship between fire behavior, the susceptibility of exposed elements, and suppression actions determines how severe a fire will be (Tedim et al., 2013). The most documented sources describe "physical damage" to highways as slides and other debris that land on roads because of disruption to their "natural state" as wildfires occur, though evidence to describe the particular features of the damage is lacking. Other wildfire research has involved case studies of slides and roadways in Seiad, California (De La Fuente & Mikulovsky, 2016), and in the hills of Portugal (Araújo Santos et al., 2020).

While the literature above details the WUI and the subsequent building damages as well as slide damaged/erosion control and rockfall activity, none of the papers identified in this research addresses the three elements of wildfire-caused highway impairment – physical characteristics, roadway impacts, and traffic impacts and their subsequent additional metrics.

STUDY AREA

Oregon, U.S. is selected for this analysis because of its regular periods of drought, **which** have become more frequent, widespread, and severe across the state. This endeavor offers a chance to constructively contribute to Oregon Natural Hazards Mitigation Plan (ONHMP; 2020) as it is routinely updated. The wildfire hazard, while formidable in Oregon, can intensify and be exacerbated by changes in other Oregon hazards such as extreme heat, drought, and high winds in the summer and autumn seasons (Richardson et al., 2022). Oregon's highway system is continuously susceptible to wildfire hazards and has experienced recent numerous blazes across the state. This analysis specifically targets three highways in Oregon that were closed for several weeks due to the 2020 Labor Day wildfires. These highways fall within the three of the eight risk assessment regions outlined in the ONHMP (2020). Each of these regions was assessed at a regional scale by profiling the characteristics, natural hazards, and vulnerabilities within the ONHMP Regions. The three highways and the wildfires that affected them are shown in Figure 1 and described in greater detail below.

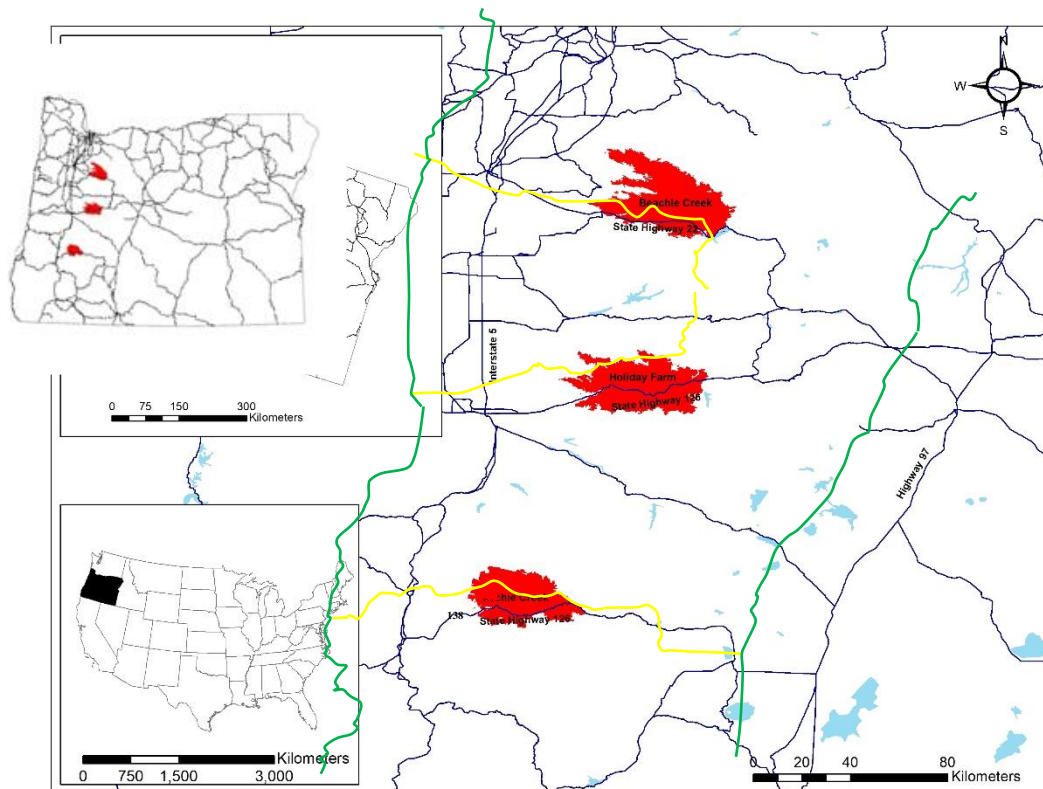


Figure 1. Map of 2020 Labor Day wildfires and highway affected in Oregon.

The Beachie Creek Fire was situated at 44.821°N and 122.88°W, near the towns of Lyons/Mehama, Mill City, Gates, Detroit, and Idanha in Marion and Linn County, Oregon's Santiam Canyon along State Highway 022. The fire started on August 16, 2020 (Comer et al., 2021), and ultimately burned 73,336 ha in total. The fire was declared contained on October 31, 2020. The Holiday Farm Fire was situated at 44.172°N, 122.231°W, near Springfield in Lane County, Oregon, along State Highway 126. According to FEMA (2020), the fire started on Monday, September 7, 2020, and burned an estimated 70,170 ha. The date of containment was October 29, 2020. The Archie Creek Fire was situated along State Highway 138 at 43.334°N and 122.788°W, near the community of Glide in Douglas County, Oregon (ESRI, 2022). According to ESRI (2022), the fire started on Tuesday, September 8, 2020, and it consumed around 53,233 ha. It was contained on Monday, November 16, 2020 (ESRI, 2022).

METHODS AND MATERIALS

Physical Characteristics

Physical parameters for this assessment included defining the length of highway impacted as well as the ADT counts during the wildfires. The length of highway impacted was a result of hazard tree damage, pavement damage, slope/rock scaling damage, and structural damage.

Data from the subject fires was provided by the Oregon Department of Transportation (ODOT) and was originally expressed in standard units, which were subsequently converted into metric units for the study. The information in the appendices was kept in standard units, while being converted to metric units throughout the study. Mile post (MP) and ADT count information was obtained through ODOT (ODOT; 2023) and interpolated to align with the various closure areas on each of the three highways. Aligning areas of highway closures with the appropriate ADT information was necessary to provide accurate ADT statistics. This included identifying the MP range limits within the highway closures during the wildfires and summing their ADTs for each range. Physical damage data were collected from ODOT's Detailed Damage Inspection Reports (DDIRs) and synthesized from the three Labor Day wildfires into a standard format (Appendices A-F).

Additional information concerning the damage to the roadways during the wildfires was obtained through the ODOT from its Oregon Wildfire Response and Recovery efforts during and after the wildfires. The physical impacts were captured, detailed, and summarized on the Federal Highway Administration (FHWA) DDIRs completed by ODOT for each highway. This information was received from ODOT on January 31, 2022 (Oregon State Highway 138 – Archie Creek Wildfire) and March 3, 2022 (Oregon State Highway 022 – Beachie Creek Wildfire and Oregon State Highway 126 – Holiday Farm Wildfire). The initial damage reports were completed over a five-month period (October 2020 – February 2021). Each physical impact is itemized, with additional detail on site location as well as a description of the damage. Figure 1 provides the wildfire locations in Oregon and facilitates comparison of the highway locations impacted in relation to the wildfire area of influence. During the Beachie Creek wildfire, Oregon State Highway 022 was closed for approximately 36 days (7 September 2020 to 13 October 2020). The Holiday Farm wildfire led to the closure of Oregon State Highway 126 for around 26 days (7 September 2020 to 2 October 2020). Oregon State Highway 138, affected by Archie Creek wildfire, experienced closure for about 14 days (8 September 2020 to 22 September 2020). The ADT associated with the wildfire was examined by comparing the ADT data for the previous five years (2015 – 2019) for each of the three highways using the same MP range noted during the 2020 wildfire occurrences.

Percentage of highway closed ($P_{CLOSEDi}$) was determined by summing the number of kilometers closed ($KM_{CLOSEDi}$) and dividing by the sum of the total kilometers of highway (T_{TOTALi}) for each highway i (Appendix G). The percentage of highway impacted ($P_{IMPACTi}$) was determined by summing the damaged number of kilometers impacted ($KM_{DAMAGEDi}$) on the three routes and dividing by the sum of the total kilometers of footprint (KM_{FOOTi}) for each highway i (Appendix G). Total kilometers of highway footprint is defined as the overall length of the highway – based upon mileposts. The reduced ADT (ADT_{REDi}) was examined by averaging the ADT data for the previous five years (2015 – 2019) for each of the three highways using the same MP range as noted above. The 2020 ADT was then divided by this five-year average to compute the percentage due to the wildfires (Appendix G).

Roadway Impacts

Roadway impacts to the three highways due to the wildfires included hazard tree removal – trees that needed to be removed (those that present a danger, either standing or fallen), pavement damage (burning asphalt concrete), slopes/rock scaling (loose hazard rocks, and vegetation), and structural damage (guardrail, signage, and delineators).

The impact of hazard trees on the roadways was assessed in terms of the highway length impacted (km) to reflect the physical damage due to hazard trees. The calculations considered the length of the highway affected by hazard trees, irrespective of the specific number of trees, while the number of trees will be part of the roadway impact assessment. Pavement damage refers to the highway's destruction caused by the fire, measured in meters. The data attained from ODOT's DDIRs was incomplete. Both the Beachie Creek and Holiday Farm fires had complete pavement damage

information. Even though the Archie Creek Fire provided the length of highway impacted, it only offered a generalization of the pavement damage and therefore could not be included in the average meters of pavement damage per kilometer of highway impacted.

Slope/rock scaling damage involves the removal/repair of loose hazard rocks, trees, and vegetation along slopes and is calculated in counts of each. While some of the data were quantitative with repairs specified within specific MPs along the damaged roadways, other reports provided generalized identification of damaged slopes along the roadways needing to be addressed for the roadways to be reopened safely without restrictions. Structural damage is mainly identified as damage to guardrails, signs, delineators along with some bridges, culverts, and retaining walls, measured in meters. While part of the data was numerical, i.e., estimated meters of damaged structures along the roadway, other reports were broader in their identification of such sites.

The number of hazard trees (HT_i) identified along the highway were divided by the total kilometers of highway (KM_{Hli}) impacted to calculate the average number of hazard trees to be removed per kilometer of highway impacted for each highway i , (TR_{KM,Hli_i}). The meters of pavement damage (M_{PDi}) were divided by the total kilometers of highway impacted (KM_{Hli}) to get the average pavement damage along highway impacted i , (A_{PDi}). For highway i (A_{SRi_i}), the average slopes/rock scaling damage were calculated by dividing the total kilometers of impacted roadway (KM_{Hli}) by the average slopes/rock scaling repairs (SR_i). Average structural damage (A_{SDi}) was calculated by dividing the total number of kilometers of impacted highway (KM_{Hli}) by the structural damage (SD_i). (Appendix G)

Traffic Impacts

The kilometers of closed highway and the kilometers of highway requiring traffic management during repair activities were both included in the traffic control statistics. The traffic control information was also obtained from DDIRs received from ODOT. The reports provided a more generalized assessment of the number of kilometers of highway that needed to be closed and the traffic management issues that needed to be resolved for the highways to be safely reopened without limits. The Wildfire Closure Status Maps included the affected mile posts as well as the dates of the road closures. Each report also included the level of road closure, which had a status of one of the following: (A) Full Closure/Evaluating Damage; (B) Critical Services; (C) Partial Opening; or (D) Open w/Ongoing Repairs.

Additional details included the reduced highway speeds experienced during various road closures as well as the work that was being done when the roads were closed. Data also included the hectares of wildfire burned and the estimated length of roadway that were closed and required traffic control throughout the wildfires. The reduced AADT on these three highways was determined by taking the AADT from the five years prior to the 2020 wildfires and comparing them against the 2020 AADT. This included identifying and matching the various MPs identified in the wildfire closure status maps along with the FHWA DDIRs and cross-checking them against the ODOT AADT information (ODOT, 2023).

The total number of hectares burned (H_{Bi}) was divided by the total number of kilometers of highway traffic control impacted (KM_{TCi}) to arrive at the average number of hectares burned per kilometers of traffic control needed for the highway i ($HB_{KM,TCi}$). The total number of hectares burned (H_{Bi}) was divided by the total number of kilometers of road closed (KM_{RCi}) to determine the average number of hectares burned per kilometers of road closure for the highway i ($HB_{KM,RCi}$). The AADT from 2020 must be deducted from the AADT from 2015–2019, which must then be divided by the AADT from 2020, in order to determine the AADT reduction ($R_{AADT_{2020_i}}$), which decreased in 2020 compared to the previous five years AADT. (Appendix G)

RESULTS and DISCUSSION

Physical Characteristics

Length of Highway Affected

The wildfires identified in this study encompassed approximately 286 km of highway, or 60.72% of the entire length of the three highways analyzed (Table 1). While this is only 2.2% of the approximately 12,875 km of the Oregon state highway system (2017 Oregon Mileage Report, 2018), all three of these highways are vital east-west connector routes between the two main north-south highway routes of Interstate 5 and Highway 97 within Oregon.

Table 1. Length of Highway Closed for the Three 2020 Oregon Fires Included in the Case Study, by Highway.

Highway Impacted	Wildfire	Length of Highway Closed (km)	Total Length of Highway Impacted (Km)	Percentage of Highway Closed during Wildfire
Hwy 022	Beachie Creek Fire	113	130	86.92%
Hwy 126	Holiday Farm Fire	37	178	20.79%
Hwy 138	Archie Creek Fire	136	163	83.44%
Total		286	471	60.72%

The information provided in Table 2 categorizes the percentage of highway damage in relation to each of the three highways footprints. The table indicates the following for each of the roadway impacts: Structural damage appears to constitute the most damage, averaging 55%, with a high of 65% and a low of 39%. Hazard trees represent the second-greatest damage component, with an average of 45%, a high of 65% and a low of 36%. Slope/rock scaling damage is the next-most type of damage, averaging 22%, with a high of 65% and a low of 0%. Finally, the least amount of damage was the actual pavement damage, which averaged 15%, with a high of 18% and a low of 12%.

Table 2. Length and Percentage of Highway Damaged.

Highway and Fire	Highway Impacted (km)	Highway Impacted by Hazard Tree Damage	Highway Impacted by Pavement Damage	Highway Impacted by Slope/Rock Scaling Damage	Highway Impacted by Structural Damage	Highway Hazard Trees Impacted	Highway Pavement Damage/Repairs Impacted	Highway Slope/Rock Scaling Damage Impacted	Highway Structural Damage Impacted
Highway Footprint	Kilometers of Damage				Percentages				
Beachie Creek Fire, Hwy 022	130	84	23	84	84	65%	18%	65%	65%
Holiday Farm Fire, Hwy 126	178	69	29	0	69	39%	16%	0%	39%
Archie Creek Fire, Hwy 138	163	58	19	19	106	36%	12%	12%	65%
Total	471	211	71	103	259	45%	15%	22%	55%

ADT Impacts

While the average ADT dropped by approximately 11% on these three highways during the wildfires, they all dropped almost identically: averaging between 11–13% during the wildfires. While not excessive, ADT exceeding 10% may attract attention due to the unplanned impact on commercial

freight vehicles as well as normal passenger commuting – both of which had to travel additional distances on detour routes around the wildfires. This is noteworthy due to the different duration each highway was closed, which averaged 25 days. While this does not appear to be a significant reduction, these routes are vital to Oregon's transportation system in terms of commerce, freight, and tourism. Again, while the information provided in Table 3 is informative, the wildfire area and the RADT do not appear to be related.

Table 3. Average Daily Traffic (ADT) Impacts during the Wildfire Event.

Highway – Wildfire	Milepost Range	ADT (2015-2019)	ADT in 2020 (during the Wildfires)	RADT
Highway 022-- Beachie Creek Fire	MP 22.40-- MP 81.51	5,857.75	5,269.56	11%
Highway 126-- Beachie Creek Fire	MP 21.40-- MP 45.37	3,896.00	3,514.60	11%
Highway 138-- Archie Creek Fire	MP 16.35-- MP 100.71	1,363.89	1,211.42	13%
Total	-	11,117.64	9,995.58	11%

Roadway Impacts

Hazard Tree Removal

There were about 40,000 trees that needed to be removed along 84 km of Oregon State Route 22, while there were about 10,000 trees that needed to be removed along 69 km of Oregon State Highway 126 and an unknown number of trees that needed to be removed along 58 km of Oregon State Highway 138 – see Table 4.

Table 4. Hazard tree removal, for the 2020 Labor Day wildfires in Oregon.

Highway	Wildfire	Number of Hazard Trees Removed	Length of Highway Impacted (km) by Hazard Trees	Hazard Trees Removed/Kilometers of Highway Impacted
Hwy 022	Beachie Creek Fire	40,000	84.00	476
Hwy 126	Holiday Farm Fire	10,000	69.00	145
Hwy 138	Archie Creek Fire	unidentified	58.00	undetermined
Total*		50,000	153	381

*Total based on Beachie Creek Fire and Holiday Farm Wildfire.

The tree removal activities along the damaged routes are compiled in Table 4. The data for the Beachie Creek and Holiday Farm fires were comprehensive, while the data for the Archie Creek wildfire were not. As a result, instead of using three sets of data points to determine the total and average, just two sets of data were used. The number of hazardous trees that needed to be removed increased with the length of route affected. According to the data, which was based on unfinished information from the Archie Creek incident, an average of 381 hazard trees needed to be removed per kilometer of highway affected by the wildfires.

Pavement Damage

The pavement damage activities along the roadways are summarized in Table 5. The average of about 27 m of pavement damage per kilometer of highway affected by the wildfires suggests that length of highway impacted is not directly related to the amount of pavement damage. While part of the information was quantitative, with estimated meters of pavement damage, other reports were broader, identifying damaged highways that needed to be corrected before the roadways could be reopened safely without limits.

Table 5. Pavement Damage, for the 2020 Labor Day wildfires in Oregon.

Highway	Wildfire	Length of Pavement Damage (m)	Length of Highway Impacted by Pavement Damage (km)	Length of Pavement Damage (m) per (km) of Highway Impacted
Hwy 022	Beachie Creek Fire	945	23	41
Hwy 126	Holiday Farm Fire	457	29	16
Hwy 138	Archie Creek Fire	unidentified	19	undetermined
Total*		1,402	52	27

*Total based on Beachie Creek Fire and Holiday Farm Fire.

Slopes/Rock Scaling Damage

For each of the three highways, Table 6 provides details on the slope/rock scaling damage. In one area along 84 km of Oregon State Highway 022 where the Beachie Creek wildfire occurred, scope assessments were necessary, along with eight (8) locations along Oregon State Highway 126, where the Holiday Farm wildfire occurred. The Archie Creek wildfire broke out in an unidentified number of locations along 19 km of Oregon State Highway 138 where scope assessment was necessary.

Table 6. Slope/Rock Scaling Damage, for the 2020 Labor Day wildfires in Oregon.

Highway	Wildfire	Number of Slopes/Rock Scaling Locations (EA)	Length of Highway Impacted by Slope/Rock Scaling Damage (km)	Number of Slope/Rock Scaling Locations (EA) per Length of Highway (km)
Hwy 022	Beachie Creek Fire	1	84.00	0.01
Hwy 126	Holiday Farm Fire	8	unidentified	undetermined
Hwy 138	Archie Creek Fire	unidentified	19.00	undetermined
Total*		1	84	0.01

*Total based on Beachie Creek Fire.

With two-thirds of the data unidentified, even a generalization of the slope/rock scaling damage is difficult to quantify or establish a basic average per kilometer affected.

Structural Damage

The specific structural damage information for each of the three highways is shown in Table 7. Highway 022 had structural damage spanning roughly 4,267 m along 84 km, while Highway 126 also had structural damage spanning about 4,267 m along 69 km necessitating repairs to guardrail, signs, and delineators,

Table 7. Structural Damage, for the 2020 Labor Day wildfires in Oregon.

Highway	Wildfire	Length of Structures Damaged (m)	Length of Highway Impacted by Structural Damage (km)	Length of Structures Damaged per Length of Highway (m/km)
Hwy 022	Beachie Creek Fire	4,267	84	51
Hwy 126	Holiday Farm Fire	4,267	69	62
Hwy 138	Archie Creek Fire	unidentified	106	undetermined
Total*		8,534	153	56

*Total based on Beachie Creek Fire and Holiday Farm Fire.

Only a portion of the data from ODO’s DDIRs was complete. Unfortunately, the full details of the Beachie Creek and Holiday Farm fires did not establish a link between the amount of highway kilometers affected and the need for structural repairs. An average of 56 m of structures needed to be repaired per kilometer of highway affected. Even though the Archie Creek wildfire data set contained the kilometers of roadway that were affected, it only presented a generalization of the structural damage and could not be considered for calculating the average length of structures damaged per kilometer of highway affected.

In addition, the Bad Banks Bridge (State Bridge #06761) at OR22, MP 36.74 – Beachie Creek wildfire, sustained damage, including structural harm to the concrete inlet, wing walls, and apron, as well as to the culvert liner and retaining wall. It also included the melting of galvanized coating off manhole covers and HDPE diversion pipes, and burned trees that could harm the bridge. There were over 4,267 m of guardrail, 119 signs, and 520 lane delineators along 69 km of Oregon State Highway 126, MP 12.7 to 56 that needed to be repaired where the Holiday Farm wildfire occurred. The damage was reported along 106 km of Oregon State Highway 138 where the Archie Creek wildfire generalized sign, guardrail, fencing, delineator posts, and mile markers and post damage without providing specific quantities.

Traffic Impacts

Traffic Control

The DDIRs gave an overview of traffic management for certain MP spans. The length of highway requiring traffic control required some interpretation of the data from ODO’s DDIRs. The findings do not indicate that wildfire size is related to the amount (length) of highway traffic control.

Table 8. Hectares Burned per Length of Traffic Control, by Highway.

Highway	Wildfire	Area Burned (ha)	Length of Highway Traffic Control (km)	Hectares Burned per Length of Highway Traffic Control (ha/km)
Hwy 022	Beachie Creek Fire	78,336	84	933
Hwy 126	Holiday Farm Fire	70,170	unidentified	undetermined
Hwy 138	Archie Creek Fire	52,233	106	493
Total*		130,569	190	687

*Total based on Beachie Creek Fire and Archie Creek Fire.

Road Closure Status

The length of road closures and the hectares burned per km of highway closures are documented in Table 9. This data was gathered using information from the 2020 Oregon wildfire closure status maps that ODOT provided. These wildfire closure maps, which are listed in appendix F, were made available to the general public during the wildfires. The data does indicate that the size of the wildfire affects how many kilometers of highway were closed or how many hectares were burned for every kilometer of closed highway.

Table 9. Area Burned per Length of Highway Road Closure, by Highway.

Highway	Wildfire	Area Burned (ha)	Length of Highway Road Closures (km)	Hectares Burned per Length of Highway Road Closure (ha/km)
Hwy 022	Beachie Creek Fire	78,336	95	825
Hwy 126	Holiday Farm Fire	70,170	56	1,253
Hwy 138	Archie Creek Fire	52,233	100	522
Total		200,739	251	800

Each of the three highways being studied in Oregon utilized road closure status maps that were updated during the 2020 wildfires. (See appendix F) Road closures fell into four categories:

- Full closure
- Critical services that allow emergency and service vehicles only
- Partial access
- Traffic restored with some ongoing repairs

Three updated corridor status maps were available for the Beachie Creek wildfire, three were available for the Holiday Farm wildfire, and two were available for the Archie Creek fire. Each provided the date, time, and MP span of the closure as well as the road closure status, the normal speed limit vs. the reduced speed limit, and the work being performed on the roadway.

Unfortunately, all the road closure status maps had unidentified information, which made the comparison of the maps challenging.

AADT Impact

The ADT decreased by around 11% during the wildfires, as previously indicated in Table #3, as a result of the varying numbers of days the highways were closed, which had an immediate impact on the highways. Table #10 is used to measure long-term trends or variations in travel demand and illustrates the long-term impact to the AADT on the same routes.

Table 10. Annual Average Daily Traffic (AADT) Impacts, by Highway.

Highway-- Wildfire	Milepost Range	Annual ADT (AADT) (2015-2019)	AADT in 2020-- (less the # of days highway closed)	AADT Decrease (2015-- 2019)--2020	RAADT
Highway 022-- Beachie Creek Fire	MP 22.40-- MP 81.51	2,138,079	1,733,685	404,394	23%
Highway 126-- Beachie Creek Fire	MP 21.40-- MP 45.37	1,422,040	1,191,449	230,591	19%
Highway 138-- Archie Creek Fire	MP 16.35-- MP 100.71	497,819	425,208	72,611	17%
Total		4,057,938	3,350,342	707,596	21%

The RAADT on these three highways was approximately 21%. This was determined by taking the AADT from the 5 years prior to the 2020 wildfires and comparing them against the 2020 AADT.

SUMMARY AND CONCLUSION

This study creates a method for analyzing historical infrastructure losses due to wildfire in Oregon, a state in the U.S. with average infrastructure, a relatively sparse population, and a likely growing vulnerability to prolonged dry spells-- averaging approximately 131 days of rainfall per year (Oregon Annual Rainfall and Climate Data, 2023). Most archival publications document how climate change affects infrastructure damage as well as the economic impacts associated with wildland fires and consist largely of residential and commercial property losses (homes, personal belongings, commercial structures, and inventory). Overall, there is a dearth of research on damage to highway infrastructure due to wildfires. To achieve the research goals, three distinctive elements were analyzed in this study -- physical roadway characteristics, roadway impacts, and traffic impacts. Each of these three elements included sub-features that measured several additional types of damage. Data analysis revealed limited relationships between the size of the wildfires, the subsequent impacts to the highways and the damage that occurred with each one.

The major results from this research can be summarized as follows:

- Physical Roadway Characteristics
 - Wildfires affected slightly less than 61% of the approximately 286 total kilometers of the three highways analyzed.

- On average, structural, hazard trees, slope/rock scaling and pavement damage is 55%, 45%, 22%, and 15%, respectively, in relation to the highway footprint.
- The RADT during the wildfires averaged about 11%.
- Roadway Impacts
 - An average of approximately 381 hazard trees were to be removed per kilometer of highway impacted by the wildfires.
 - An average of approximately 27 m of pavement damage/repairs occurred per kilometer of highway impacted by the wildfires.
 - An average of approximately 1.0 (EA) instances of slope/rock scaling damage occurred per 100 km of highway impacted by the wildfires.
 - An average of approximately 56 m of structural damage occurred per kilometer of highway impacted by the wildfires.
- Traffic Impacts
 - An average of approximately 687 ha burned per kilometer of highway traffic control during the wildfires.
 - An average of approximately 800 ha burned per kilometer of highway road closures during the wildfires.
 - The RAADT due to the wildfires was about 21%

The observed physical roadway characteristics, roadway impacts, and traffic impacts provide valuable information about the vulnerability of highways to wildfires. The analysis of hazard trees, pavement damage, slope/rock scaling, and structural damage indicate areas that require special attention in future wildfire mitigation strategies. These results directly contribute to improving infrastructure resilience and wildfire management strategies. This information will help designers create highways that are more prepared to resist the effects of wildfires. Additionally, integrating the results into existing wildfire risk assessment models will enhance their accuracy and enable more informed decisions regarding land use planning.

Despite the practical benefits of this study, several limitations need to be addressed in future research. The evaluation focused on only three highways in Oregon affected by the 2020 Labor Day wildfires, although many others were affected simultaneously. Supplementary research should include the analysis of more highways within the geographical region. In addition, each of the three distinctive elements analyzed in the study – physical characteristics, roadway impacts, and traffic impacts, along with their sub-features, all had missing information in one form or another. Additional limitations include the ADT information gathered for this report. While this report analyzed the previous five years of AADT information prior to the 2020 Labor Day wildfires, analysis of more years could enhance the accuracy of the calculations and the association between the reduction in ADT and wildfire impacts.

Future research would benefit from more complete information in each of the categories. Some of the challenges that this research faced included initially obtaining the research data, extracting individual elements/sub-features from the data, and recognizing that much of the physical damage information provided for each wildfire was consistently incomplete. Despite these drawbacks, the results of this study will help decision-makers estimate potential physical wildfire roadway damage in other regions in addition to Oregon.

CONTRIBUTION

Based on the number of ha burned and the length of highway affected by the wildfires, this research developed averages, gathered, and analyzed the data, and developed the initial method for assessing and foreseeing the potential damage from wildfires to highways. This includes physical damage; roadway impacts as well as traffic impacts to the highways. While this information is preliminary, local, and state government leaders can use its applications to assess wildfire damage and aid in determining annual roadway damage forecasts. This paper will be the first to project probable roadway infrastructure damage loss at the micro-scale (three (3) roads) – using Oregon as an example.

Author Contributions: Christiansen developed the methodology, collected, and analyzed the data, and developed the initial text. Mostafiz expanded the literature review, edited the text, prepared Figure 1 and helped to develop specific equations. Friedland provided original ideas and advice on the overall project methodology and edited the text. Rohli edited early and late drafts of the text. Dunn provided advice on the project and edited the text. Al Assi edited late drafts of the text.

Appendix A – Hazard Tree Removal

Wildfire Site	Date of Report	Site Location	Description of Damage	Emergency Repair Estimated Costs	Permanent Repair Estimated Costs
Beachie Creek Fire DDIR Site Number D03-001	11/20/2020	OR22 (Highway 162 North Santiam Highway) MP 13 - 65	Catastrophic wildfire damage from Beachie Creek Fire to approximately 40K trees along highway requiring immediate removal	\$4,000,000	\$0
Holiday Farm Fire DDIR Site Number D5-001	11/19/2020	OR126 (Highway 015) MP 12.7 to 56	Catastrophic wildfire damage from the Holiday Farm Fire to approximately 10K trees along highway requiring immediate removal	\$1,000,000	\$0
Archie Creek Fire DDIR Site Number D07-001	12/1/2020	North Umpqua Hwy, OR138 East, MP 17 to 28.8	Hazardous trees: weakened standing and fallen trees.	\$605,000	\$1,083,000
Archie Creek Fire DDIR Site Number D08-006	12/1/2020	North Umpqua Hwy, OR138 East, MP 28.8 to 43	Hazardous trees: weakened standing and fallen trees	\$605,000	\$1,695,000
Archie Creek Fire DDIR Site Number D08-013	1/12/2021	North Umpqua Hwy, OR138 East, MP 73 to 83	Hazardous trees: weakened standing and fallen trees.	\$75,000	\$151,000

Appendix B – Pavement Damage

Wildfire Site	Date of Report	Site Location	Description of Damage	Emergency Repair Estimated Costs	Permanent Repair Estimated Costs
Beachie Creek Fire DDIR Site Number D03-007	12/14/2020	OR22 (Highway 162 North Santiam Highway) MP 37 - 51	Catastrophic wildfire damage to approximately 3100 centerline feet of paving on OR22 caused by Beachie Creek Fire.	\$155,700	\$0
Holiday Farm Fire DDIR Site Number D5-005	12/15/2020	OR126 (Highway 015) MP 29 to 47	Catastrophic wildfire damage to approximately 1500 centerline feet of pavement on OR 126 from the Holiday Farm Fire	\$272,960	\$0
Archie Creek Fire DDIR Site	12/1/2020	North Umpqua Hwy, OR138 East, MP 17 to 28.8	Pavement was damaged by fire burning on the road	Information Not Provided	\$156,000

Number D07-005			and during fire cleanup efforts.		
Archie Creek Fire DDIR Site Number D08-012	12/1/2020	North Umpqua Hwy, OR138 East, MP 29.3; 29.4; 30.1; 31.3; 32.0; 34.5; 35.3	Pavement was damaged by fire burning on the road and during fire cleanup efforts.	Information Not Provided	\$186,000

Appendix C – Slope/Rock Scaling Damage

Wildfire Site	Date of Report	Site Location	Description of Damage	Emergency Repair Estimated Costs	Permanent Repair Estimated Costs
Beachie Creek Fire DDIR Site Number D03-004	11/20/2020	OR22 (Highway 162 North Santiam Highway) MP 13 - 65	Catastrophic wildfire damage to highway from Beachie Creek Fire requires slope scaling and -assessment to assess corridor slope damage.	\$15,900	\$0
Beachie Creek Fire DDIR Site Number D03-006	12/16/2020	OR22 (Highway 162 North Santiam Highway) MP 34 - 43	Catastrophic wildfire damage to highway from Beachie Creek Fire requires rock scaling to remove loose hazard rocks, trees, and vegetation on 8 slopes between MP 34 - 43	\$588,125	\$0
Beachie Creek Fire DDIR Site Number D03-008	2/22/2021	OR22 (Highway 162 North Santiam Highway) MP 40 - 44	Catastrophic wildfire damage to highway from Beachie Creek Fire requires rock screen repairs to damaged screens on slopes between MP 40 - 44	\$930,286	\$0
Beachie Creek Fire DDIR Site Number D03-009	2/22/2021	OR22 (Highway 162 North Santiam Highway) MP 40 - 60	Catastrophic wildfire damage to highway from Beachie Creek Fire requires rock screen repairs to damaged screens on slopes between MP 40 - 60	\$1,165,000	\$0
Holiday Farm Fire DDIR Site Number D5-002	11/25/2020	OR126 (Highway 015)	Rock Scaling/Slope Assessment	Information not provided	\$0
Archie Creek Fire DDIR Site Number D07-004	10/29/2020	North Umpqua Hwy, OR138 East, MP 24.85	Unstable slopes causing rock, tree, and other material to fall onto the roadway	\$4,000	\$9,500
Archie Creek Fire DDIR Site Number D07-006	12/2/2020	North Umpqua Hwy, OR138 East, MP 26.42	Unstable slopes causing rock, tree, and other material to fall onto the roadway	Information not provided	\$11,000
Archie Creek Fire DDIR Site Number D08-009	12/1/2020	North Umpqua Hwy, OR138 East, MP 34.02	Unstable slopes causing rock, tree, and other material to fall onto the roadway	\$12,500	\$27,000

Archie Creek Fire DDIR Site Number D08-010	12/1/2020	North Umpqua Hwy, OR138 East MP 37.9	Unstable slopes causing rock, tree, and other material to fall onto the roadway	\$2,500	\$6,500
Archie Creek Fire DDIR Site Number D08-011	12/1/2020	North Umpqua Hwy, OR138 East MP 31.7	Unstable slopes causing rock, tree, and other material to fall onto the roadway	\$5,000	\$214,850
Archie Creek Fire DDIR Site Number D08-016	12/2/2020	North Umpqua Hwy, OR138 East MP 33.45	Unstable slopes causing rock, tree, and other material to fall onto the roadway	Information not provided	\$8,000
Archie Creek Fire DDIR Site Number D08-017	12/2/2020	North Umpqua Hwy, OR138 East MP 34.3	Unstable slopes causing rock, tree, and other material to fall onto the roadway	Information not provided	\$8,000
Archie Creek Fire DDIR Site Number D08-018	12/2/2020	North Umpqua Hwy, OR138 East MP 36.9	Unstable slopes causing rock, tree, and other material to fall onto the roadway	Information not provided	\$15,000

Appendix D – Structural Damage

Wildfire Site	Date of Report	Site Location	Description of Damage	Emergency Repair Estimated Costs	Permanent Repair Estimated Costs
Beachie Creek Fire DDIR Site Number D03-002	11/20/2020	Bad Banks Bridge (State Bridge #06761) at OR22 (Highway 162 North Santiam Highway) MP 36.74	Catastrophic wildfire damage to Bad Banks Bridge due to Beachie Creek Fire, to include structural damage to the concrete inlet, wing walls, and apron, culvert liner, and retaining wall; galvanized coating melted off of manhole cover; melted HDPE diversion pipes and burned trees that pose a damage to the bridge.	\$386,880	\$0
Beachie Creek Fire DDIR Site Number D03-005	11/24/2020	OR22 (Highway 162 North Santiam Highway) MP 13 - 65	Catastrophic wildfire damage from the Beachie Creek Fire to approximately 14K linear feet of guardrail, signs, and delineators on OR22E requiring repair.	\$490,980	\$0
Holiday Farm Fire DDIR Site Number D5-004	11/19/2020	OR126 (Highway 015) MP 12.7 to 56	Catastrophic wildfire damage from the Holiday Farms Fire to approximately 14k linear feet of guardrail, 119 signs, and 520 Lane delineators on OR126	\$888,780	\$0

Archie Creek Fire DDIR Site Number D07-003	12/1/2020	North Umpqua Hwy, OR138 East, MP 17 to 28.8	Sign, Guardrail, fencing, delineator posts, and mile markers and post damage.	\$177,500	\$310,000
Archie Creek Fire DDIR Site Number D08-008	12/1/2020	North Umpqua Hwy, OR138 East, MP 28.8 to 83	Sign, Guardrail, fencing, delineator posts, and mile markers and post damage.	\$212,500	\$347,700

Appendix E – Traffic Control

Wildfire Site	Date of Report	Site Location	Description of Damage	Emergency Repair Estimated Costs	Permanent Repair Estimated Costs
Beachie Creek Fire DDIR Site Number D03-003	11/20/2020	OR22 (Highway 162 North Santiam Hwy) MP 13 - 65	Traffic control and pilot car operations for highway closure due to Beachie Creek Fire.	\$282,300	\$0
Holiday Farm Fire DDIR Site Number D5-003	11/25/2020	OR126 (Highway 015)	*Erection and removal of barricades and detour signs *Flagging and pilot cars during the emergency period	Information not provided	Information not provided
Archie Creek Fire DDIR Site Number D07-002	12/1/2020	North Umpqua Hwy, OR138 East, MP 17 to 28.8	Traffic Control for Road Closure	\$260,000	\$335,000
Archie Creek Fire DDIR Site Number D08-007	12/1/2020	North Umpqua Hwy, OR138 East, MP 28.8 to 83	Traffic Control for Road Closure	\$285,000	\$510,000

Appendix F – Road Closure

Highway	Date of Map	Times of Map	Milepost s	Road Closure Status	Standard Speed	Mileposts	Reduced Speed	Work Performed
OR-126 Corridor	9/15/2020	12:35 PM	12.7 - 47.3	Level A - Full Closure / Evaluating Damage	55 mph	unidentifie d	unidentifie d	unidentified
OR-126 Corridor	9/15/2020	4:40 PM	12.7 - 47.3	Level B - Critical Services	55 mph	unidentifie d	unidentifie d	unidentified
OR-126 Corridor	Unknown	Unknown	13 - 47	Level D - Reduced Speed	55 mph	28 - 38	45 mph	Active work zone with damaged or missing guardrail and signs and logs/debris piled on roadside
OR-022 Corridor	9/15/2020	12:35 PM	22 - 81	Level A - Full Closure / Evaluating Damage	55 mph	unidentifie d	unidentifie d	unidentified
OR-022 Corridor	9/15/2020	4:40 PM	22 - 81	Level B - Critical Services	55 mph	unidentifie d	unidentifie d	unidentified

OR-022 Corridor	Unknown	Unknown	22 - 81	Level D - Open with Ongoing Repairs	55 mph	33 - 63	40 mph	Active work zone with damaged or missing guardrail and signs and logs/debris piled on roadside
OR-138 East Corridor	9/15/2020	12:35 PM	21 - 83	Level A - Full Closure / Evaluating Damage	55 mph	unidentifie d	unidentifie d	unidentified
OR-138 East Corridor	9/16/2020	8:15 AM	21 - 83	Level B - Critical Services	55 mph	unidentifie d	unidentifie d	unidentified

Appendix G - Highway Physical Damage Equations

Hazard	Equation
Percentage of Highway Closed	$P_{CLOSEDi} = \frac{KM_{CLOSEDi}}{KM_{TOTALi}} \times 100$
Percentage of Highway Impacted	$P_{IMPACTi} = \frac{KM_{DAMAGEDi}}{KM_{ADT_{2020i}}} \times 100$
Average Daily Traffic (ADT) Impacts during event	$ADT_{REDi} = \frac{ADT_{(2015-2019)i}}{HT_i}$
Average Hazard Trees to be removed per KM of Highway Impacted	$A_{PDi} = \frac{T_i}{KM_{HHi}}$
Average Pavement Damage per KM of Highway Impacted	$A_{SDi} = \frac{KM_{HHi}}{KM_{HHi}^{BI}}$
Average Slopes/Rock Scaling Damage per KM of Highway Impacted	$HB_{KM.TCi} = \frac{KM_{HHi}}{KM_{HHi}^{BI}}$
Average Structural Damage per KM of Highway Impacted	$HB_{KM.RCi} = \frac{KM_{HHi}}{KM_{RCi}}$
Average # of HA Burned per KM of Traffic Control	
Average # of HA Burned per KM of Road Closure	
Annual Average Daily Traffic (AADT) Impact	$R_{AADT_{2020i}} = \frac{AADT_{(2015-2019)i} - AADT_{2020i}}{AADT_{(2015-2019)i}}$

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