Managing Alaska's Road-Dust Problem: A Model for Road Dust–Impacted Regions

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Abstract: Poor air quality in Alaska's remote communities due to road dust is one of the top environmental concerns of residents in these communities. Most communities are disconnected from the road network, with community roads that are predominantly unpaved. In Alaska, high costs limit widespread paving of roads, leaving communities to rely on alternative dust control strategies. The goals for this study were to assess the magnitude and impact of the dust problem in rural Alaska and use a diversity of experience, including regulatory, research, engineering, and cultural, to develop a road-dust management approach for rural Alaska. The plan incorporates different levels of dust management: institutional controls, road watering, chemical dust suppressants, and road surface stabilization. Geographical zones where use of each different dust management level will be most appropriate are identified based on rainfall frequency. Approximately 50% of Alaska's communities can manage road dust with institutional controls and road watering. Many of the road-dust management ideas presented are transferable to other global regions that experience similar economic and community access challenges as Alaska. **DOI: 10.1061/JTEPBS.0000314.** *© 2020 American Society of Civil Engineers.*

Introduction

There are 190 remote communities disconnected from the road system in Alaska. One of the top environmental concerns for most of these communities is the degradation of air quality due to dust from local unpaved roads (National Tribal Air Association, 2017 status of tribal air report, unpublished report). Plumes of dust that loft behind vehicles traveling along these unpaved roads are composed of particles that can range from as small as the sub-micrometer size to several hundred micrometers (Pinnick et al. 1985; Hinds 1999). The impact of the loss of these particles from the road surface to the atmosphere is profound. The smallest of particles negatively affect human health. Moreover, dust composed of the entire range of particle sizes impacts driver safety, the environment, quality of life, and community economics.

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Note. This manuscript was submitted on October 30, 2018; approved on July 26, 2019; published online on February 5, 2020. Discussion period open until July 5, 2020; separate discussions must be submitted for individual papers. This paper is part of the ***Journal of Transportation Engineering, Part A: Systems***, © ASCE, ISSN 2473-2907.

The uniqueness of Alaskan communities brought about by their remote locations and their prevalence of unpaved roads requires a strategy for managing road dust. The goals of this study are to assess the magnitude and impact of the road-dust problem in rural Alaska and use a diversity of experience, including regulatory, research, engineering, and cultural, to develop a road-dust management strategy for rural Alaska. The resulting road-dust management plan is the first such plan presented in the accessible literature that addresses a very large regional area encompassing multiple different climatic zones. Although this plan addresses a region of cold climate, many of the road-dust management ideas presented here are transferable to other global regions that may experience similar economic and community access challenges as Alaska. Greening (2011) discussed the disproportionate cumulative effects of road dust on citizens of developing countries. Many of the road-dust management ideas presented here will be helpful to these regions.

Compared with most communities in the contiguous United States, Alaska's remote communities are unique. The primary access to these communities for residents and visitors as well as cargo is by air. During the short summer season, shipping supplies such as fuel and large equipment by barge is an option for communities on the river system. Residents also travel between villages by boat in the summer and snow machine in the winter. Local roads are unpaved for a vast majority of these communities. Quality of these roads range from properly designed and maintained gravel roads to trails worn into the tundra. Homes, schools, and health clinics are typically located close to the road (Fig. 1).

Discontinuous or continuous permafrost underlies a large portion of Alaska. The presence of permafrost presents challenges to maintaining roads and managing road dust. Removal of the vegetation and top layer of tundra to construct roads disturbs the thermal balance, causing thawing of ice-rich permafrost in many cases. With the creation of void spaces in the underlying soil from thawing of ice features in the permafrost comes subsidence of the ground surface. During freezing periods, ground may heave as ice forms in the top layers of soil. Both the subsiding and heaving of the ground surface creates an uneven driving surface on most roads in Alaska. Moreover, the movement of the ground surface

J. Transp. Eng., Part A: Systems, 2020, 146(4): 04020019

Fig. 1. (Color) Typical unpaved road in an Alaska rural community. (Image by David L. Barnes.)

impacts drainage from the road prism, hastening degradation of the road. Owing to the rough nature of the roads, many rural Alaskan community residents prefer all-terrain vehicles (ATVs), also commonly known as four-wheelers. The combined influences of improperly designed roads, the degradation of the roadway due to freezing and thawing soils, the general lack of proper maintenance, and the use of ATVs with their aggressive tires results in road dust and dusty conditions in most rural Alaskan communities.

Background

Sources and Production of Unpaved Road Dust

Multiple sources contribute to generation of dust from unpaved roads. As vehicles pass over the surfacing aggregate, the shearing force created at the interface between vehicle tires and the aggregate break the forces binding particles, resulting in generation of road dust. The weight of the vehicle also results in particle-to-particle grinding as tires roll over the aggregate. This repetitive grinding breaks down particles and generates dust (Pinnick et al. 1985). Airborne dust from other sources (river shores, glacial till, and unpaved lots, among others) can settle onto the road surface, resulting in lofting as vehicles pass. Finally, deposition of dust attached to vehicles entering the road is another likely source of dust.

Mechanically generated road dust is composed of solid particulate matter lofted into the air by vehicle traffic and is capable of staying suspended in the air column for seconds to hours. The size range of these particles varies from sub-micrometer to more than 100 μm in particle diameter (Hinds 1999).

The USEPA categorizes plumes of dust generated as vehicles pass across unpaved road surfaces as fugitive dust owing to the lack of discharge of these particles from a confined flow stream (USEPA 1995). Two mechanisms are responsible for creating fugitive dust from unpaved roads. First, the aerodynamic drag of moving vehicles causes a turbulent wake with air speeds that result in lift forces at the road surface (Sehmel 1973; Moosmüller et al. 1998; Nicholson and Branson 1990). These forces are particularly evident when observing plumes of dust created by large vehicles, such as delivery trucks, traveling on dusty paved and unpaved roads. The profiles of such large vehicles cause turbulent air to be pushed to the sides of the moving vehicles at wind speeds that overcome the forces that are resisting the soil particles from becoming airborne (Moosmüller et al. 1998; Gillies et al. 2005). These turbulent wind patterns result in plumes of dust emanating from the sides of the vehicle.

The action of vehicle tires on the road surface results in the second mechanism for the creation of fugitive dust. Forces created during vehicle acceleration, assentation of grades, and traversing curves in the roadway result in the entrainment of particles from the road surface into the moving vehicle's turbulent wake (Barnes and Connor 2017). Excessive vehicle acceleration and rapid assentation of steep grades increase dust production due to sliding of the vehicles tires on the unpaved surface. Turbulence created by the compression and expansion of air beneath tires as they roll over the road surface is an additional mechanism that entrains particles into the vehicle's turbulent wake (Nicholson and Branson 1990). Accelerated degradation of unpaved road surfaces occurs in areas that are subjected to these vehicle forces, such as road intersections and curves, causing increased dust production over time.

Road dust is still a problem during winter even with the constant snowpack that persists during October through April in most areas of Alaska. To create safe driving conditions on unpaved roads, grader operators will often remove the snow on roads down to the aggregate surface. Under these conditions, sublimation removes ice from the exposed surface aggregate pore space, leaving nothing to

J. Transp. Eng., Part A: Systems, 2020, 146(4): 04020019

bind small aggregate particles. The loss of the particle-to-particle binding created by ice in the aggregate pore space results in the creation of fugitive dust by vehicle traffic.

Impact of Road Dust

The USEPA (2017b) estimated that unpaved roads released over 10^{10} kg of particulate matter smaller than 10 μm in aerodynamic size (PM_{10}) to the atmosphere in the United States in 2014. This emission makes up 51% of all emissions from stationary sources of PM_{10} air pollution in the United States (road dust is considered a stationary source by the USEPA). Exposure to these small particulates has associated health effects. The USEPA (2009) discussed the health effects related to short-term exposure to particulate matter with aerodynamic diameters between 2.5 and 10 μm ($PM_{10-2.5}$). In that study, the USEPA (2009) analyzed multiple epidemiological, controlled human exposure, and toxicological studies and concluded that these studies are suggestive for relationship between short term exposure to $PM_{10-2.5}$ and cardiovascular effects, respiratory effects, and mortality.

Disease-causing microbial contamination attached to dust is also a potential health issue related to dust (Rosas et al. 1997). A number of rural communities in Alaska are without piped water and sewers due to complications of providing utilities to homes in continuous and discontinuous permafrost regions. In these communities, residents collect human waste in their homes in 18.9 L (5-gal.) plastic buckets with plastic liners. Once the buckets are full, residents self-haul these containers on the back of their ATVs to a dumpsite for disposal. In a field study, Chambers et al. (2009) determined that in these communities, the open dumpsites used for human-waste disposal and spillage of human waste in transport are source areas for the migration of contamination back into the community by vehicle traffic. Under these conditions, in communities that are also impacted by road dust, there is a potential for this contamination to be further distributed attached to dust particles.

Several researchers have documented the environmental and ecological impact of road dust (Tamm and Troedsson 1955; Eller 1977; Farmer 1993; Zhu et al. 2014). The impacts of road dust are particularly acute in tundra ecosystems, such as in Alaska. Due to the lack of sources for road aggregate materials in many areas, communities must obtain aggregate from distant sources, resulting in placement of nonnative material in tundra environments. The chemical composition of this material may in some cases impact native tundra vegetation by altering soil pH and nutrient content (Everett 1980; Spatt and Miller 1981; Walker and Everett 1987; Auerbach et al. 1997; Myers-Smith et al. 2006). Impact to the structural integrity of roads impacted by changes in tundra vegetation may follow due to alterations in drainage patterns. In permafrost zones, reduction of vegetation coverage on the road shoulders result in changes in the insulating capability of the ground cover, causing permafrost degradation and subsequent road instability.

Dust impacts safety in two different ways. On the dustiest of roads, dense dust clouds from leading vehicles can greatly reduce sight distances of following vehicles to less than safe stopping distances (FHWA 1998). Reductions in visibility also endanger pedestrians (including cyclists), who are at risk of vehicle–pedestrian collisions (Greening 2011). Additionally, loss of small particles that bind surface aggregate together leads to degradation of the road surface and the development of corrugations (washboards), which can result in loss of driver control (Lunsford and Mahoney 2001; Jones et al. 2013; Skorseth et al. 2015).

Degradation of road surfaces has economic impacts as well. The Federal Highway Administration (FHWA) noted that as much as 25 mm of surface gravel may be lost annually from dusty roads, resulting in an annual aggregate replacement of approximately 7×10^4 kg/km (FHWA 1998). The Alaska Department of Transportation and Public Facilities (ADOT&PF) noted similar losses on the Dalton Highway (the highway to Prudhoe Bay) during the 1980s. Burningham and Stankevich (2005) used data from the World Bank database to show that resurfacing costs for two-lane aggregate roads can range between 43% and 87% of total road maintenance costs.

Dust Measurements in Alaska

To quantify the dust problem in Alaskan communities, the Alaska Department of Environmental Conservation (ADEC) conducted air monitoring in northwestern and western regions of Alaska using high-volume samplers. ADEC selected these communities based on their known challenges with road dust. ADEC obtained these measurements between 2003 and 2005. Fig. 2 shows the location and population of each community.

Fig. 3 shows measurement results, and Table 1 provides the summary statistics and the average annual daily traffic (AADT) count for each location. During the summer months, forest fires impact the air quality in many Alaskan communities. Fig. 3 excludes measurements that may have been impacted by fire smoke, as noted by the high-volume sampler operator. For the less populated communities (Noatak, Ambler, Noorvik, and Buckland) the AADT counts reported by ADOT&PF are 2016 estimates (ADOT&PF 2016). The ADOT&PF conducts AADT counts for larger communities (Kotzebue and Bethel) every 3 years. The AADT values in Table 1 are averages of each street measured (or estimated) AADT in each community.

The most salient result shown in Fig. 3 is the number of exceedances in the PM_{10} national ambient air quality standard (NAAQS) established by the USEPA (not to exceed 150 $\mu g/m^3$ averaged over 24 h). Moreover, there are a number of days at all locations where the PM_{10} concentrations were over 55 $\mu g/m^3$. According to the USEPA's Air Quality Index, moderate air quality conditions occur when PM_{10} concentrations averaged over 24 h range between 55 and 150 $\mu g/m^3$. Moderate air quality conditions impact groups with existing respiratory diseases such as asthma.

The national PM_{10} mean obtained from 339 sites across the contiguous United States during the same period as the measurements made in the Alaska communities (2002–2005) ranged from 79.60–104.37 $\mu g/m^3$ (USEPA 2017a). Although the mean value measured in the Alaska communities is generally lower than the national mean, the difference is the number of exceedances in the NAAQS for PM_{10} and the fact that the smaller Alaska villages achieve high PM_{10} values despite the low AADT values. From the results in Fig. 3 and Table 1, it is clear that these communities have frequent episodes of poor air quality caused by excursions in PM_{10}.

Solutions to Road Dust in Alaska

Solutions to road dust span from proper road design to driver behavior changes and suppression of dust by applying water or chemicals to the road surface. Effective dust management starts with well-designed and maintained roads. Separate from other factors, inadequate aggregate gradation, malformed road crown, and lack of drainage will negatively impact the stability of any unpaved road, resulting in raveling, corrugations, and potholes. Dust-control suppressants are less effective on unpaved roads that have these types of structural problems.

Two main gravel road design and maintenance factors govern the ability to manage dust on unpaved roads: drainage and aggregate properties. Proper drainage off the road surface and away from

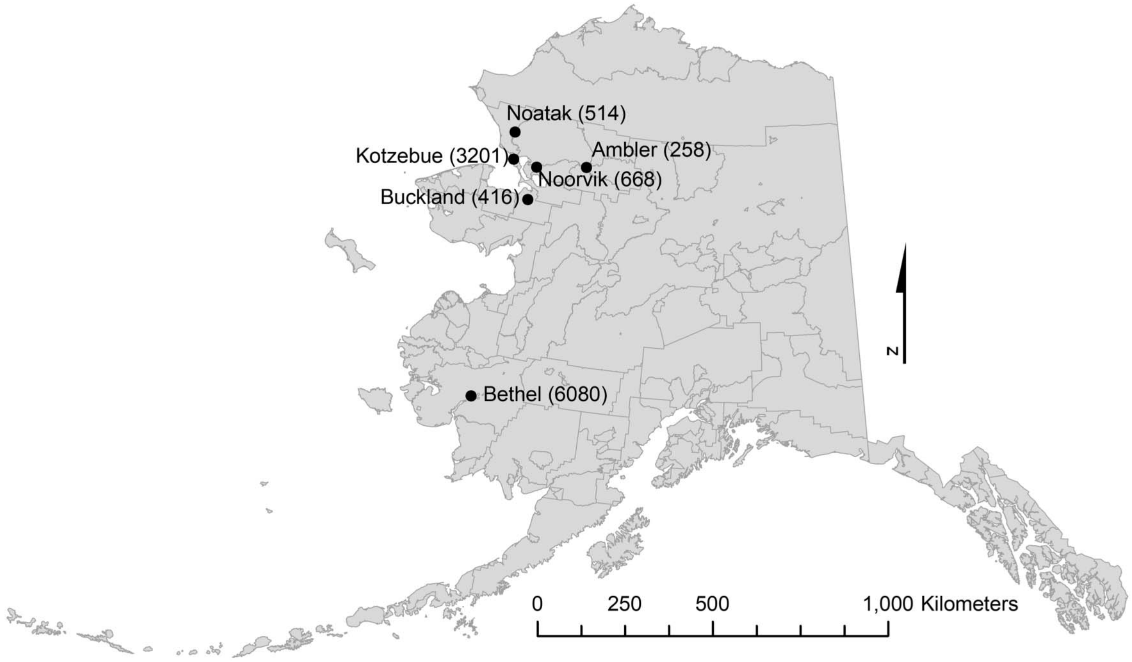

Fig. 2. High-volume sampler monitoring locations and population of each community monitored.

the road prism is critical to a well-performing road and hence to dust management (FHWA 1998). Water that accumulates in ponds on or around roadway prisms produce elevated soil-moisture contents in the road's structural layers. These high moisture contents weaken the ability for roads to carry a load, resulting in the formation of potholes, as shown in Fig. 1 (Skorseth et al. 2015). Ultimately, fugitive dust production increases from these degraded roads. Unfortunately, too often, budget constraints or poor road management result in the postponement or oversight of drainage maintenance. Moreover, it is not uncommon for Alaskan communities to lack the capability to create proper drainage. Many isolated communities do not have the necessary equipment. The communities that may have equipment may not have trained personnel to properly operate and maintain the equipment. However, drainage issues should be a priority focus for unpaved roads because maintaining the surface, including reduction of dust, is often impossible if the drainage issues are not adequately addressed.

Selection of the right aggregate material for the roadway is the second requirement. Traffic in most Alaskan communities is low, and the vehicles are generally lightweight. Consequently, the load-carrying capacity of community roads is generally much lower than in more populated areas. This attribute generally means that the structural layers can be thinner. However, planners should follow some general rules. Aggregate gradation is a key material property for both the base layers and surface course. Poorly graded aggregate that does not have a good representation of grain sizes necessary to compose a functional surface course results in degradation of the road surface (Skorseth et al. 2015). This degradation manifests itself as corrugations and raveling. For any climatic region, aggregate material must be compatible with the environment, including freezing and thawing cycles and rainfall conditions. Ideally, considering Alaska's climate, all but the surface layers should be nonfrost-susceptible. Nonfrost-susceptible soils are those that have silt and clay contents less than approximately 8%, giving these soils a low potential for frost heaving. Skorseth et al. (2015) provided a thorough discussion on gravel road construction and maintenance, and Jones et al. (2013) discussed surface-course aggregate properties as they relate to chemical dust control. Governments for rural communities should develop or adopt specifications for their gravel roads that includes road prism profile and aggregate gradation for base and surface-course materials.

Institutional Controls and Behavior Change Strategies

For any unpaved road, institutional controls and other behavior-change strategies are viable means of reducing the amount of fugitive dust produced from unpaved roads. Several studies have shown the influence that vehicle speed has on fugitive dust production from paved and unpaved roads (Nicholson et al. 1989; Etyemezian et al. 2003; Gillies et al. 2005). Aggressive driving also eventually results in increased dust production owing to the damaging impact of increased shearing forces on the road surface. Many communities do not have speed limits, and those that do may be challenged with limited law enforcement. Enforcing speed limits in these communities will take a shift in social norms. Because everyone typically knows each other in these small communities, nobody wants to tell their friend and neighbor that they are driving improperly. That said, some communities impacted by road dust are educating their citizens on the relationship among road dust, vehicle speed, and aggressive driving, as well as health and safety impacts. Citizens in the rural community of Bethel, Alaska, are attempting to address the problem of road dust by educating the community about controlling vehicle speed. They have posted their own speed-limit signs and produced localized educational material (Demer 2017). The Nulato Tribal Council worked to slow down drivers by posting formal road signs with the words "Slow: Dust Sensitive Area."

Using promotional campaigns, communities can also encourage residents to use alternative modes of transportation such as walking and bicycling on dusty days. Community leaders could choose to proactively alert citizens on days when there is a potential for severe road-dust conditions to exist. Prolonged periods without precipitation, low humidity, warm temperatures, and stable atmospheric conditions are characteristic weather conditions on dusty days. Communities could adopt a flag system to inform citizens of road-dust conditions. Using this system, a colored flag could

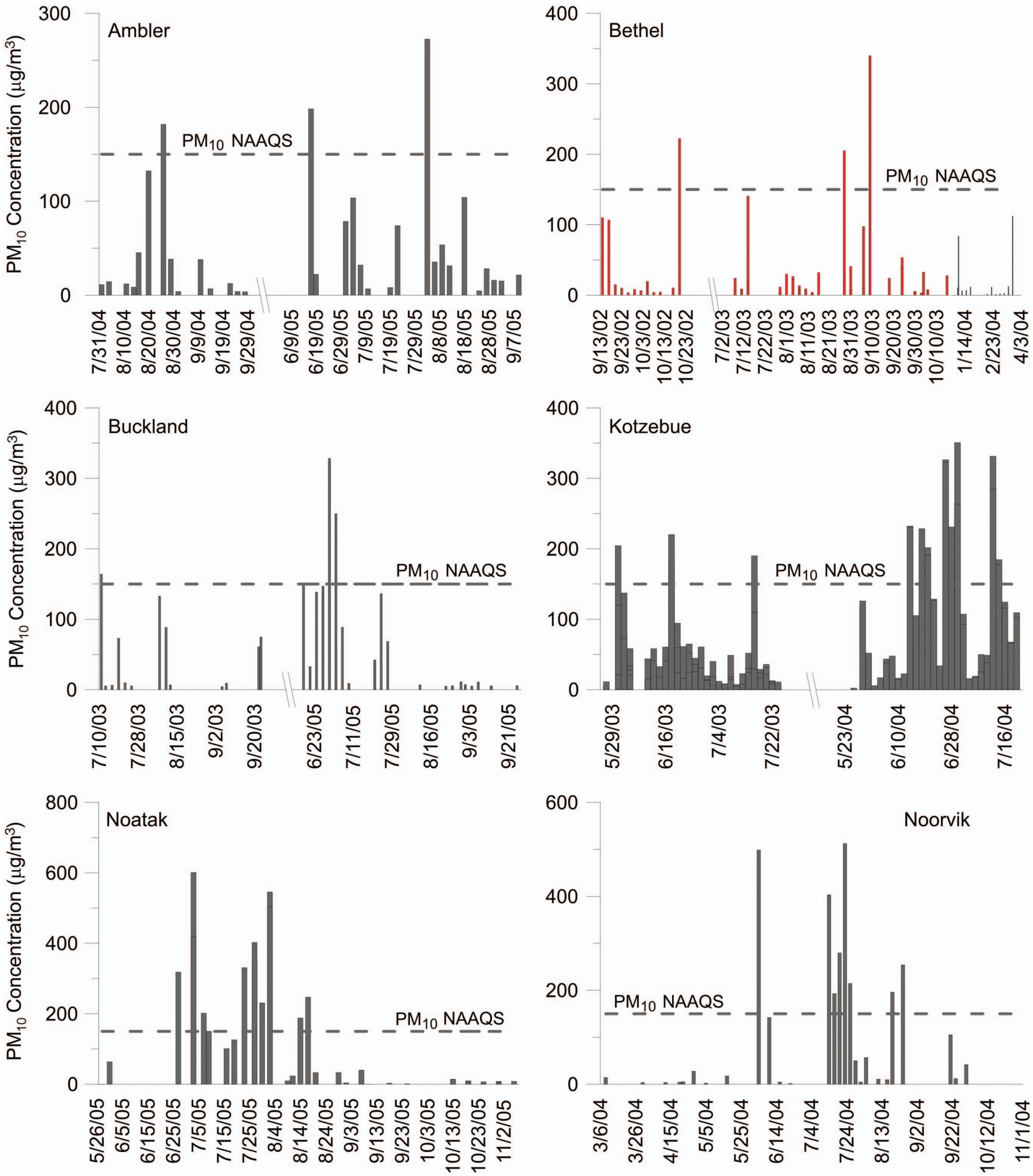

Fig. 3. (Color) PM_{10} concentrations in monitored communities.

Table 1. High-volume PM_{10} measurement statistics

Location	Number of measurements	Mean ($\mu g/m^3$)	Standard deviation ($\mu g/m^3$)	Maximum ($\mu g/m^3$)	Days exceeding (%) 55 $\mu g/m^3$ (%)	Days exceeding (%) 150 $\mu g/m^3$ (%)	AADT
Ambler	32	51	64.7	273	25	9	25
Bethel	61	34	61.0	340	15	5	3,770
Buckland	45	64	83.1	328	40	11	17
Kotzebue	190	57	72.7	351	29	11	894
Noatak	40	130	172.9	601	43	33	15
Noorvik	35	43	76.3	374	23	9	30

be flown in central locations such as the school and the community center, alerting citizens that dusty conditions exist and to limit motorized vehicles travel. These type of education and outreach are low-cost methods of changing attitudes in the community to create shared responsibility for dust management and behavior changes that can have immediate results.

Another method of influencing driving habits that minimize the creation of road dust is to train drivers during the time they are applying for a driver's license. In Alaska, drivers who live in rural communities can apply for an off-highway license instead of standard driver's license. Off-highway driver's license holders are restricted to roads that are not connected to the State's highway system. Drivers applying for this type of license follow the same steps to apply for a regular license, except no skills (road) test is required. To teach proper unpaved-road driving habits that will reduce dust production, the State could either require a skills test focused on proper vehicle handling on unpaved roads, or at the minimum, provide educational material on how to reduce the creation of dust when driving on unpaved roads.

Road-Dust Suppressants

Properly designed and constructed unpaved roads are a necessity for controlling road dust, and institutional controls and behavior changes are inexpensive and relatively simple methods of road-dust abatement. However, many unpaved roads need additional means of controlling dust. Short of paving, road managers can control dust through the application of road-dust suppressants. The application of water to unpaved roads is the oldest means of controlling dust. Indeed, *A Treatise on Highway Construction* (Byrne 1893) discussed when and how to water roads to "lay dust." However, dust control effects using water are short lived given high rates of water evaporation on warm, sunny, and hence dusty, days. Dust control may be as short as 1-h or less depending on temperature, wind, relative humidity, and soil type. The short-term effectiveness of water to suppress dust has caused this means of controlling dust to be primarily favored for construction sites where long-term dust control is not required. However, owing to relatively low traffic volume on most rural Alaska community roads and the shortness of the summer season, road watering may be appropriate for communities with infrequent periods where road-dust levels are unacceptable.

Communities that experience unacceptable dust levels at a greater frequency than what can be managed with community education, institutional controls, or road watering may need to rely on chemical dust suppressants. Skorseth et al. (2015) claimed that nearly 200 dust-suppressant products are commercially available. Table 2 categorizes the many different products into broad groups.

Alaska has approximately 26,200 km (16,300 mi) of certified public roads, which includes roads maintained by the ADOT&PF, boroughs, and municipalities, Alaska Tribes, and other state and federal agencies. Of these road kilometers, 16,362 (62%) are unpaved. Calcium chloride ($CaCl_2$) is the most used chemical dust suppressant in Alaska. As an example, the ADOT&PF applies calcium chloride to gravel portions of the Dalton Highway annually. Many boroughs also apply $CaCl_2$ to unpaved roads annually. However, few rural communities use salts (calcium and magnesium chloride) to control road dust in their communities; the use of this type of dust suppressant in rural communities has increased over the last 7 years.

The ADOT&PF has tried several other chemical dust suppressants besides salts in Alaska, with varying success. Due to lack of sufficient clay content in most of Alaska's soils, products that require a certain amount of clay in the soil, such as lignosulfonates and electrochemical stabilizers, are not effective in Alaska, and attempts to use these products have not been successful. In the past, topical applications of liquid asphalt, either in a neat application or as an emulsion, have been used to reduce dust. In general, these applications have worked to a limited extent.

In 2001, ADOT&PF began experimenting with synthetic fluids to control dust on gravel runways in rural Alaska. A synthetic fluid is a petroleum product that has undergone at least one intended major chemical transformation in its manufacturing process. The purpose of this synthesis is to remove hydrocarbons harmful to human health and the environment. One of ADOT&PF's main goals for these trials was to reduce maintenance costs on remote runways where aggregate costs can be as high as 40 times the cost incurred in more accessible regions. ADOT&PF has successfully treated multiple runways with synthetic fluids across Alaska. In addition, a few villages have applied synthetic fluids to their unpaved roads in an attempt to control road dust.

Barnes and Connor (2014) used a mobile monitor to determine that, if applied correctly on proper aggregate, applications of synthetic fluids on gravel runways will control fugitive dust from runways for as long as 2 years. Airplane traffic is light on most rural Alaska runways. Owing to the small number of planes using these runways, the primary mechanism for attenuation of the effectiveness of synthetic fluid to control fugitive dust is most likely drainage of the fluid out of the top few centimeters of the surface aggregate. In contrast, from testing on unpaved roads, Barnes and Connor (2017) found that synthetic fluids effectively controlled fugitive dust on unpaved roads for approximately 1 year. They concluded that the primary mechanism causing attenuation of synthetic fluids to control fugitive dust from unpaved roads is the mechanical shear forces created at the interface between vehicle tires and the road. The aggressive nature of vehicle tires, especially all-terrain vehicle tires, seems to result in a shorter life expectancy in comparison with the primarily gravity-drainage attenuation mechanism found on gravel runways.

Results from surveys of rural communities on their road-dust management practices conducted by the ADEC over the last 11 years indicated that some rural communities are managing dust with either chemical dust suppressants or water (unpublished results). Because of the low number of responses, it is difficult to draw specific conclusions about dust-suppressant usage trends across Alaska. The results do suggest a possible increase in the

Table 2. Road-dust palliative categories

Chemical dust-suppressant group	Suppression mechanism	Common products
Water-attracting salts	Binding of silt and clay particles by capillary forces resulting from adsorption of water from the atmosphere into the treated aggregate	Calcium chloride and magnesium chloride[a]
Organic nonbituminous binders	Weak bonds created between aggregate particles and clay dispersant increasing aggregate compaction	Lignosulfonates, tall oil, pine tar, and molasses[b,c]
Synthetic oils	Binding of silt and clay particles by capillary forces created by the added synthetic fluid	Proprietary formulations
Electrochemical stabilizers	Changes characteristics of clay-particles increasing compaction	Enzymes, sulfonated oils, and ionic[c]
Bitumen asphalt and tar	Coats or seals particles	Cutback asphalts, emulsified asphalts
Synthetic polymer emulsions	Mechanically binds soil and aggregate	Polyvinyl acetate and vinyl acrylic

[a]Active at relative humidity greater than 30%.
[b]Less common products include animal fats and vegetable oils, which have little binding action.
[c]Products require a certain amount of clay in the aggregate to be effective.

number of communities using chemical dust suppressants and a possible reduction in the use of water to control road dust. These results also show that 40% of the total number of communities that responded to the 3 years of surveys (excluding repeat responders) are willing to try controlling dust on their community roads with chemical suppressants. Many of these communities will require the equipment necessary to properly apply dust suppressants. Of the responders that indicated that a dust problem exists in their community, concerns over human health effects and environmental impacts are the top reasons why they are not currently willing to try chemical dust suppressants. This is a valid concern and needs to be addressed.

An additional concern about the use of chemical dust suppressants expressed in the surveys conducted by ADEC was the lack of understanding of how to apply different dust suppressants. To assure the proper application of chemical dust suppressants, the State could create a certified dust-suppressant applicator program. This program would oversee the training and certification of applicators who would then provide their services to communities seeking chemical road-dust suppression. Such training could also include instruction on institutional controls so the applicators could work with the community on the best practices to preserve the effectiveness of the applied chemical.

Road-Surface Stabilization

Researchers have experimented with the use of polymers on Alaskan roads surfaced with marginal materials such as sandy soils. On a test section in south central Alaska, Connor and Collins (2012) were able to stabilize a road section surfaced with windblown sand using polymer, cement, and plastic fiber. The result was a stabilized dust-free road that lasted 6 years without grading. The disadvantages of this method of managing dust are the high cost and the need for specialized equipment not available in most Alaskan villages. Topical application of polymers to unpaved roads can provide a hard dust-free driving surface. However, these researchers noted that in time, potholes will form in the road surface requiring grading and reapplication. In contrast, for roads treated with $CaCl_2$ that form potholes, road managers could typically just rework the road surface to eliminate the potholes and then regrade the surface without reapplication of additional $CaCl_2$.

Most communities in rural Alaska prefer asphalt concrete streets. Indeed, a growing number of larger villages in Alaska are paving their main streets. As one might expect, the cost of paving in remote Alaskan communities is extremely high. Further, these communities have to maintain the paved roads, which is expensive owing to heaving and subsiding ground created by formation of ice in soils and by thawing permafrost. These environmental impacts cause problems for both paved and unpaved roads. The cost of construction and asphalt concrete paving in rural Alaska can be as high as $2 million per kilometer. The high cost can be attributed in part to the cost of improving the road to support asphalt pavement, mining and shipping aggregate from suitable material sources, and the cost of shipping the necessary equipment to the community.

Proposed Road-Dust Management Plan

A road-dust management plan for rural Alaska villages should be a logical combination of behavior and institutional controls, dust suppression, and stabilization. A common denominator between these three dust-management options is proper road design and maintenance as well as changes to driving behaviors.

Although every community needs to have a good gravel road maintenance program and a good driving habit education program, the level of dust management required for each community is different depending on the magnitude of the community dust problem. As discussed, several factors control the amount of dust produced from unpaved roads. Owing to the ability of soil moisture to suppress the lofting of dust, precipitation is one of the key factors impacting the level of dust management required for a rural Alaska community. Generally, wetter locations such as communities in southeast Alaska require less intensive dust-management plans than dry areas in the interior and Arctic regions of Alaska. However, even the wetter locations found in southeast and southwest Alaska may have a number of extended periods without rainfall that may result in dusty conditions.

To provide some overall guidance, the total number of possible days in an average summer on which a community may experience fugitive dust from unpaved roads is used to recommend the appropriate level of dust management. A day where the production of fugitive dust from an unpaved road is possible is known as a potential dust day. The levels of dust management based on the total number of potential dust days in a location are classified as institutional controls (Level 1), road watering with institutional controls (Level 2), chemical dust management with institutional controls (Level 3), or stabilization (Level 4). A potential dust day is defined as a day following at least 2 consecutive days without measurable rain. The amount of time it takes for a gravel road to dry to a state where traffic produces dust following a rain event is dependent on several factors: gradation of the aggregate comprising the road surface, amount of rainfall, humidity, and the amount exposure to direct sunlight the road receives. Considering all these factors is near impossible for a management plan that addresses a large expanse such as Alaska and may be unnecessary in the categorization of large areas into dust-management zones. Therefore, the number of days following a rainfall event that fugitive dust forms from a typical road surface with aggregate is based off the authors' experience working on road-dust issues throughout Alaska. These observations have shown that unpaved roads can begin to dry to a point that vehicle traffic produces small dust plumes in less than half a day following a rain event. However, it takes a few days before the road is dry enough to produce substantial fugitive dust from vehicle traffic. Given the variability in all the factors that control creation of fugitive dust following a rain event, 2 consecutive days is selected as the time span required before vehicle traffic can generate substantial dust plumes on typical unpaved roads in Alaska.

Discounting winter dust, unpaved roads can become dusty in as early as May and may stay dusty until the end of September, depending on the region of Alaska. Five years (2013–2017) of rainfall data for 127 first-order and cooperative meteorological stations across Alaska were obtained. From these data, the mean number of annual potential dust days that occur at each location between May 1 and September 30 (known as the dust season) were determined. The maximum number of potential dust days during this time is 151. The average percentage of potential dust days is used to categorize each location into one of the four dust-management levels. Fig. 4 shows the category level for each meteorological station location and the general zones for each dust-management level. The levels identified for each region are recommended minimum levels of dust management.

As Fig. 4 shows, the distribution of these meteorological stations across Alaska is uneven. The densest station coverage is near the population centers of Anchorage and Fairbanks. Western and northern Alaska have the fewest stations as a function of land area. As expected, southeast Alaska experiences the lowest percentage of dust days in the dust season, and the interior and Arctic regions experience the highest.

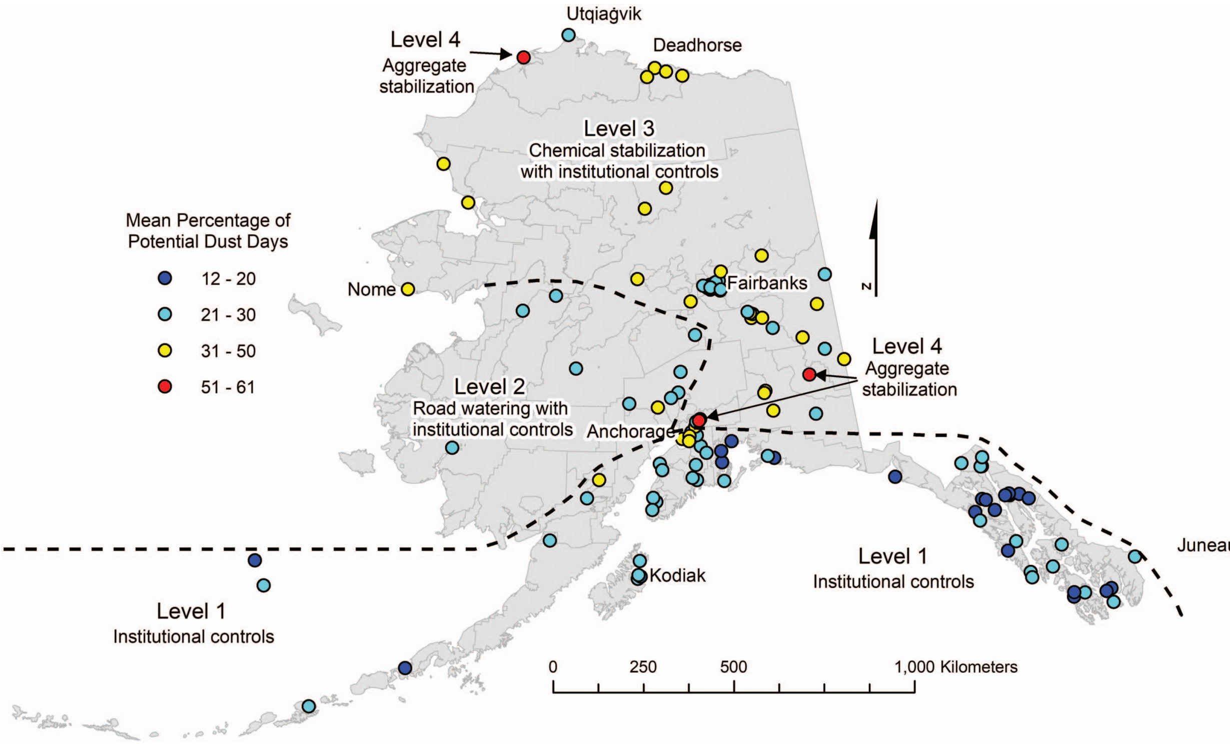

Fig. 4. (Color) Alaska dust management zones.

Level 1 Communities

It seems reasonable to assume that communities experiencing up to 20% potential dust days during the dust season can manage road dust through institutional controls. These communities are defined as Level 1 communities. Level 1 communities span southwest and southeast Alaska. Many roads are paved in this region of Alaska due to the prevalence of good-quality aggregate. However, some communities still rely on unpaved road networks. These communities should develop a plan for implementation of institutional controls that includes a community outreach program, signage to remind drivers of dusty road segments near sensitive populations such as elders' homes, schools, and health clinics, and recommendations for behavior changes during very dry dusty periods. The community may also want to develop a system to alert the community that dry dusty conditions exist and residents should limit their use of vehicles.

Level 2 Communities

Communities with 21%–30% potential dust days during the dust season require more than institutional control to manage dust. These communities, defined as Level 2 communities, should consider managing road dust with road watering in combination with the institutional controls described for Level 1 communities. These communities are located mainly in the western part of the state.

Watering trucks are the standard method of applying water to unpaved roads. However, communities may not own a watering truck or have the means of operating and maintaining the equipment. An alternative for smaller communities is a trailer holding a several hundred-gallon tote plumbed to a pump attached to a spray bar towed by an ATV. The spray bar should be fitted with nozzles that spray water down on the road in overlapping fan patterns. Guidelines for use of water to control dust recommend a pattern of regular watering during dusty periods as opposed to less-frequent heavy watering. Heavy watering may result in a soft and muddy road surface and may cause the fine material (silt and clay) that binds aggregate together on the road surface to wash away, eventually resulting in increased fugitive dust (Foley et al. 1996).

Level 3 Communities

Communities with 31%–50% potential dust days during the dust season require a more aggressive dust management strategy. These locations are defined as Level 3 communities, which includes the interior and parts of southcentral Alaska. These communities should consider developing a defined strategy for applying chemical dust suppressants. This plan should include testing to determine which suppressant works best for community roads, suppressant application rates, frequency of application, selection of which roads are to receive treatment, shipping logistics, and maintenance of chemically treated roads. Comparing different products to determine the most appropriate chemical dust suppressant for a community based on performance and public acceptance is recommended. Performance can be informally evaluated by photographing the production of dust behind vehicles on each test section on a frequent basis (every 2 weeks) and qualitatively comparing the size of the dust plume created behind the vehicle with time.

Salt-type products in liquid form and synthetic fluid–type dust suppressants are topically applied products. Communities can apply these products using the same type of spray-application equipment as described for applying water to roads. This equipment is relatively inexpensive to purchase and maintain. It is important that a proper application of these products should produce overlapping fluid spray fan patterns to achieve complete and even coverage on the road surface. Classic water trucks that apply large amount of water to roads, such as used in the construction industry, are not appropriate for applying chemical dust suppressants. Application rates (volume per road surface area) should be determined by field

J. Transp. Eng., Part A: Systems, 2020, 146(4): 04020019

testing or laboratory testing prior to ordering and shipping the product. Jones et al. (2013) provided a thorough discussion on chemical dust-suppressant application.

In the development of a dust management plan that uses chemical dust suppressants, one should take into consideration that treatment of every road in a community with a dust suppressant may not be required. Communities should treat main roads that receive high volumes of traffic, such as near the community store and roads that pass in front of sensitive areas such as the community school, elders' homes, and health clinic. All other roads in the community can be left untreated or receive less-frequent applications of dust suppressant if high costs make it challenging to treat all roads.

Roads treated with chemical dust suppressants still require maintenance. Communities should reapply dust suppressants on a more frequent basis (at a lighter application rate than the original rate) to areas that experience greater shear forces (curves, grades, and traffic control zones) to maintain dust control. Moreover, at intersections with untreated connecting roads, communities should plan to apply dust suppressant for 15–20 m from the intersection onto the intersecting untreated road. Because the effectiveness of chemical dust suppressants decay with time, communities should plan both financial and logistically to reapply chemical dust suppressants to all treated roads on a regular basis. Barnes and Connor (2017) found reapplication of chemical dust suppressants may be required as frequent as yearly. Experience with the product will dictate reapplication rates and frequency.

Shearing forces created by quick accelerations and decelerations, high vehicle speeds, and aggressive driving decreases the longevity of dust-control suppressants effectiveness on treated gravel roads. Hence, to preserve the effectiveness of applied dust suppressants, communities should develop and follow an institutional control program incorporating ideas previously discussed.

Level 4 Communities

Communities that experience greater than 50% potential dust days during the dust season have an acute road-dust problem. These communities should consider a soil stabilizer, such as asphalt or polymers, for at least the community roads that receives the highest volume of traffic. Several communities scattered about Alaska fall into this category.

Conclusions

Rural Alaska communities are dusty in the summer. Emission of fugitive dust from unpaved community roads result in particulate matter concentrations in many communities exceeding the NAAQS for PM_{10}. Managing road dust in Alaska's rural communities takes planning and a commitment from the community to develop and carry out a dust management plan. Communities can manage their road dust by implementing behavioral and institutional controls, applying water, chemically treating unpaved roads with a dust suppressant, or stabilizing the road surface with asphalt or possibly polymers. Although controlling road dust with chemical dust suppressants or stabilizing the surface aggregate with polymers or asphalt may be attractive to communities, results from this study show that not every rural community in Alaska needs to resort to these expensive options. Many communities can adequately manage road dust by institutional controls and gain other benefits such as improved driver and pedestrian safety.

Use of institutional controls to manage road dust requires community buy-in, education, and behavior changes. The main responsibility of community residents in a road-dust management plan is to control their vehicle speed. Speed control not only reduces the amount of fugitive dust created by moving vehicles but also slows the degradation of road surfaces and, on chemically treated roads, prolongs the effective life of these treatments. Many rural regions around the world face the same air quality issues due to road dust as Alaska's communities. Many of the ideas presented here are applicable to development of road-dust management plans in impacted regions outside of Alaska.

Data Availability Statement

All data and codes generated or used during this study are available from the corresponding author by request (high-volume sampling results, precipitation data, and potential dust days spreadsheet).

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