Capacity Building for

Mongolian Ministry of Environment and Green Development (MEGD) in Relation to Biodiversity and Conservation in the Southern Gobi Desert

Final Report: Annex E: Traffic Considerations for Wide-ranging Endangered Migratory Ungulates in the Southern Gobi

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1. INTRODUCTION

The Gobi Desert is the fifth largest desert in the world, stretching over much of southern Mongolia and northern China (Figure 1). The Gobi supports many important species, several of which are listed as rare or endangered such as the khulan (Asiatic wild ass) and the goitered gazelle. The importance of the area for these species can be emphasized by considering that Mongolia's Steppe and Gobi regions support the world's largest remaining populations of Asiatic Wild Ass or khulan (Kaczensky et al. 2015), Goitered gazelle (Mallon 2008a) and Mongolian gazelle (Mallon 2008b).

Figure 1: Gobi Desert Location

The South Gobi region can be defined as the Mongolian portion of the Central Asian Gobi Desert ecoregion, as delineated by World Wildlife Fund (WWF) Mongolia Program Office for the National Gap Assessment (Chimed-Ochir et al. 2010), and its four sub-ecoregions: the Eastern Gobi, the Gobi-Altai, the Southern Gobi-Altai and the Dzungarian Gobi.

This region has developed rapidly over the past several years, with 288 active mining leases in April 2014, of which the largest are the Energy Resources (ER) Ukhaa Khudag (UK) coal open pit, the Tavan Tolgoi (TT) coal mine, the Oyu Tolgoi (OT) copper mine, and the Ovoot Tolgoi coal mine.

Mining products from these mines are currently shipped by truck primarily to China. To handle this freight traffic, there are two recently constructed paved roads that cross the southern Mongolia border near the Gobi Small Protected Area B. Additionally, some trucks travel on dirt track over the open desert (Figure 2).

Figure 2: Trucks Traveling over the Open Desert (Photo taken in 2013).

Except for work camps near these mines, the region is sparsely populated with low vehicle ownership. According to the 2010 census, population density in people per square kilometer is 0.4 in the Omnogovi Aimag and 0.5 in the Dornogovi Aimag. Aside from the two newly constructed roads mentioned previously, the other roads in the area are primarily dirt track and gravel paved roads with modest non freight traffic.

The potential negative impact on wildlife in the Gobi Desert due to the increased traffic and new transportation infrastructure is a major concern, creating additional barriers in the critical habitat of migratory ungulates (TBC & FFI 2011, Lkhagvasuren et al. 2011).

The European Bank for Reconstruction and Development (EBRD) is involved in several of these mining projects in this region and funded this capacity building project to help ensure the long range sustainability of wildlife populations despite the continued mining and transportation infrastructure development in the Gobi.

Other efforts of the capacity building project include development of GIS tools to support compliance with biodiversity offset regulation, development of GIS database to support habitat connectivity modeling and training in soil analysis. This report focusses on the traffic and transportation infrastructure as it relates to wildlife. The report:

- Provides a summary of the current and expected wildlife impacts of the transportation system in the Gobi Desert in southern Mongolia (primarily focusing on the area of increased mine development and a focus on the target species),
- Summarizes the existing transportation system and current and expected traffic levels,
- Discusses potential mitigation methods for transportation and traffic impacts on wildlife, and
- Addresses the management of road dust for unpaved roadways.

This report is intended as a draft version for discussion. Feedback on this report, additional meetings with stakeholders and data collection will further inform this report. This report will be finalized prior to the end of the project scheduled for spring 2016.

2. WILDLIFE ISSUES OF HIGHWAYS AND RAILROADS

In the South Gobi region, habitat fragmentation by roadways and railways is having the greatest impact on wide-ranging endangered migratory ungulates including khulan and goitered gazelle.

Khulan, or Asiatic wild ass (Equus hemionus) occur in three populations across the South Gobi region, with the largest population of approximately 35,000 in the southeastern Gobi, in Omnogovi, Dundgovi and Dornogovi aimags, and two smaller populations of approximately 11,000 in Dzungarian Gobi and 6,000 in the Transaltai Gobi (Kaczensky et al. 2015, Reading et al. 2001, Kaczensky et al. 2011). Radio-collared Khulan have been measured to have home ranges from 18,000 to 70,000 km^2(Kaczensky et al. 2011). There is one recorded instance of a collared khulan that traveled 12 km per day along the fence barrier of the Trans-Mongolian Railroad.

Black-tailed gazelle or goitered gazelle (Gazella subgutturosa) move over short distances in search of water and pasture during spring, autumn and dry summers. Herds cover 10-30 km per day in the winter (Mallon & Kingswood 2001). Black-tailed gazelle are capable of migrating distances of 100-250 km (CMS/UNEP 2008).

Mongolian gazelle (Procapra gutturosa) are more common in Eastern Mongolia, but the range extends west to Bayanhongor Aimag. The home range of Mongolian gazelles can range from 14,000-32,000 km^2 annually (Olson et al. 2010).

In Mongolia, grassland productivity and water availability is highly variable seasonally and inter-annually due to the variable climate (von Werden et al. 2010). The movements of khulan and gazelle in the South Gobi can be referred to as nomadic movements as they are not necessarily predictable in space or time, following irregular patterns of precipitation and vegetation productivity (Olson et al. 2010, Kaczensky et al. 2015, Ito et al. 2013b).

There are other wildlife in the area that are impacted by roads. However, khulan, Mongolian gazelle, and goitered gazelle are the core species of concern and represent good "umbrella species" For the movement of other wide ranging species. If roads are mitigated for umbrella species, other species will benefit. Other ungulates that would benefit are mentioned here.

- Argali (Ovis ammon) occur in the Mongolian Altai Mountains and in isolated areas in the Southern Gobi region but are not as wide ranging in their movements (Harris and Reading 2008). Argali home ranges are much smaller than those of khulan and gazelles; they average 57 km^2 and can range from 30-80 km^2 (Reading et al. 2005). Argali may not have pronounced migration or nomadic movements.
- Siberian ibex (*Capra sibirica*) are widespread across Mongolia. While Ibex have been observed near the OT mine site (Huijser et al. 2013), it is not considered a focal species for this project.
- Bactrian camel (Camelus bactrianus ferus) current range in Mongolia is fully protected in Ikh Gobi A Special Protected Area (SPA) and not hindered by current infrastructure (Lkhagvasuren et al. 2011).
- Saiga antelope (Saiga borealis) range is peripheral to the South Gobi region, lying north of the Gobi Altai Mountains in the Great Lakes Depression in Govi-Altai and Khovd Aimags.

- Gobi bear (Ursus arctos gobiensis) population is less than 50 individuals. The current range is in Ikh Gobi A SPA fully protected and not hindered by current infrastructure (Reynolds et al. 2010).

Figure 3 is a common construct for discussing the different types of ecological impacts roads can have on wildlife. The five impacts shown are described briefly followed by a more detailed discussion of issues in the Gobi Desert:

1. Vegetation will not grow on the road surface. The loss of habitat due to the actual paved road surface is a minor issue in the Gobi Desert.
2. The barrier effect, reducing habitat connectivity and hindering wildlife movement is likely the biggest impact of roads in the Gobi Desert on migratory species. To add clarity, the barrier effect discussion consists of both the impact of the infrastructure in the absence of traffic and the impact of the traffic itself.
3. Animal mortality from collisions with vehicles does not appear to be an issue currently in the Gobi, but could become a major concern as traffic increases.
4. Beyond the road surface, habitat is degraded some distance from the roadway due to sight, noise and pollutants from traffic and the roadway. There are two major concerns here. One is road dust from unpaved roads. The other is the visual presence of traffic, which may cause wildlife avoidance a long distance from the roadway.
5. Although not a direct impact of roads, increased access created by building roads can lead to increase poaching and other human activities that can impact the long term sustainability of wildlife.

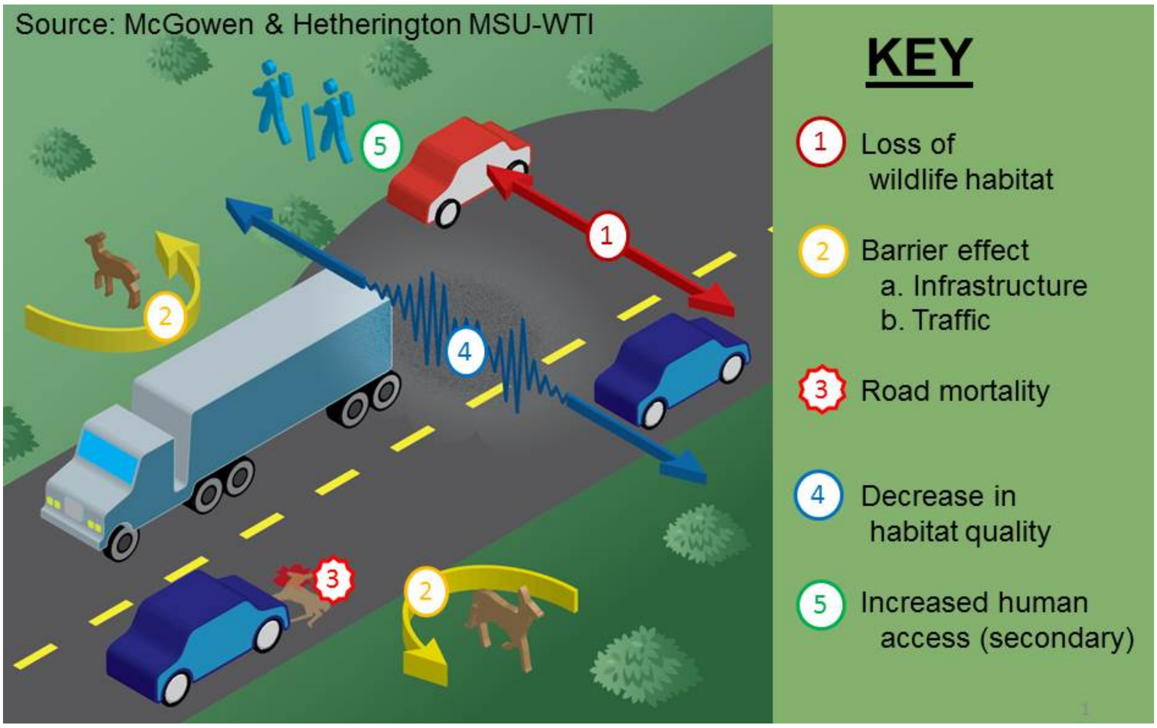

Figure 3: Types of Impacts Roads have on Wildlife

2.1. Direct Loss of Habitat

Considering the current and planned road density, the total land area lost to road surface is very small. If 10 m wide paved roads are 10 km apart, and 10 by 10 km square area has 20 km length of road, the total land area lost represents only 0.2 percent of the land area (Figure 4).

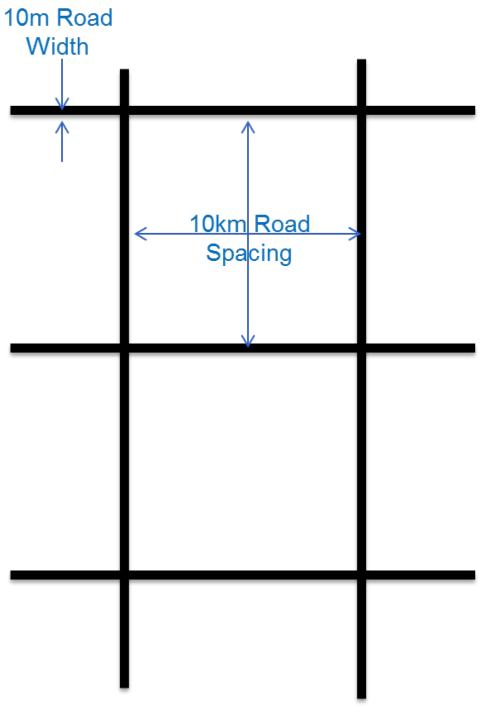

Figure 4: Direct Habitat Loss Example

In fact, constructing a paved road on an over-the-desert travel corridor will likely result in an increase in habitat because it will consolidate traffic onto a narrower corridor. When no paved roads exist, vehicles often travel on bunched parallel tracks rather than on a single track (Figure 5). According to Keshmat et al. (2013) these travel corridors average widths of 30-125m, with one example that was 900m wide.

Figure 5: Example of Over-the-Desert Travel Corridor with Several Paths

2.2. Infrastructure as Barrier

The wildlife barrier created by the pavement surface (in the absence of traffic) is likely minimal. After the construction of the Oyu Tolgoi Road, animal sightings were recently made near and on both sides of the road (Figure 6). Recent collar data has also shown regular crossings of the OT-GS Road by khulan (personal communication Petra Kaczensky, September 2015). For roads, the primary wildlife barrier is caused by traffic (discussed further in the next section).

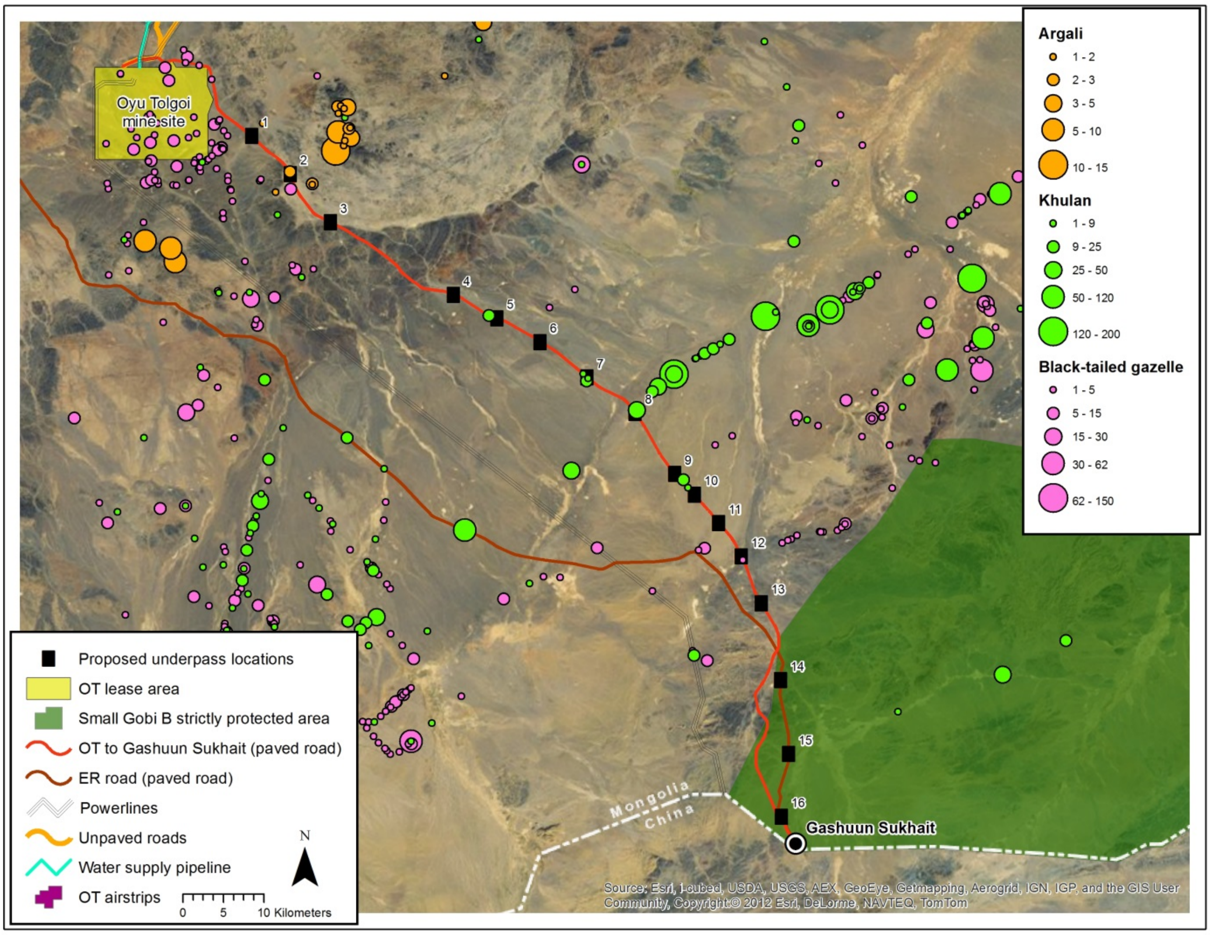

Figure 6: Ungulate Sightings for Transect Studies (OT Report)

Railroad infrastructure (even in the absence of train traffic) is a different story. Fencing along the existing railroad is a barrier, and large fill and cut slopes on partially constructed railroads may become a barrier.

Existing fencing on the Trans-Mongolian Railroad has been shown to be a barrier and to cause mortality due to fence entanglements (Lkhagvasuren et al. 2011; Kaczensky 2006; Kaczensky et al., 2011).

Efforts are underway to fix the existing fencing problem and set standards to limit and/or mitigate fencing along future railroads. Not only is this a habitat fragmentation issue, but mortality is also significant for Mongolian gazelle. Refer to Olson (2012) and Agency of Standardization and Metrology (2014) for guidance on fencing mitigation.

Another potential issue is large cut and fill slopes on railroads. The rolling resistance of a train wheel to rail is about $1/10^{th}$ that of a rubber tired truck to pavement. Thus trains can coast more easily down minor downhill grades and may require them to apply the brakes, wasting energy. Because of desire for flat grades to minimize rail fuel cost, there are typically taller fill and cut slopes on railroads than on paved roads.

The existing railroad does not seem to have as many of these slopes, so there is no historic evidence of tall fill and cut slopes creating a barrier. Partially constructed railroad lines near

Sainshand (will run east-west) and paralleling the UK-GS Road (example in Figure 7) have several sections with fill and cut slopes several meters high. These should be studied to determine potential impact to habitat fragmentation.

Figure 7: Fill Slope for Partially Constructed Railroad Parallel to the UK-GS Road

When the road or railroad has no fencing, short fill and cut slopes, and when there is low traffic, there is no evidence that the infrastructure itself is a barrier.

2.3. Traffic as a Barrier

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For most ungulates, as vehicle traffic on a roadway (or railroad) increases, the roadway becomes more of a barrier causing habitat fragmentation (Figure 8). The exact shape and thresholds of the curve in Figure 8 are not known, but related research has provided some indications.

- For pronghorn (Antilocapra Americana), Gavin and Komers (2006) found increased vigilance of animals around 200-300 vehicles per day (vpd). The road avoidance behavior in relation to traffic increased when a fawn was present in the herd. Birth season for black-tailed gazelle is May and early June, while for khulan it is mid-June through mid-July (Dorjdorem S., OT biodiversity supervisor, personal communication).
- Summaries of research for a variety of ungulates in North America and Europe suggest that the barrier effect is noticeable around 2,000 vpd (Sawyer & Rudd, 2005; Clevenger & Huijser, 2011).
- Traffic volumes of more than 4,000 vpd may create strong barriers to wildlife movements in Europe (Mueller & Berthoud 1997)
- For pronghorn, Dodd et al. (2011) found near permanent barrier of a roadway with 10,000 vpd

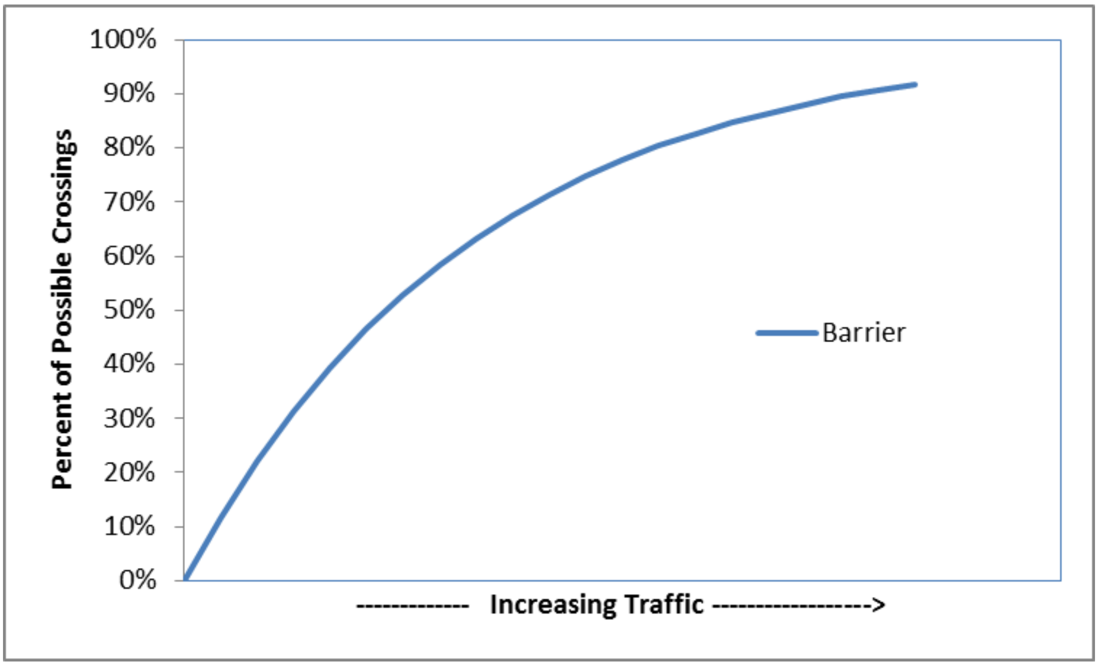

Figure 8: Traffic Level Impact on Connectivity

These traffic thresholds are likely lower for khulan and goitered gazelle because of their high avoidance of humans (developed further in the Habitat Degradation Section). Based on fleeing distances and speed, TBC and FFI (2011) estimate a serious barrier effect for khulan at 400 vehicles/day and a complete ecological barrier at 1,000 vehicles/day. It should be noted that this is based on assumptions about gaps between vehicles and the likelihood of khulan accepting those gaps.

This relationship between traffic and habitat fragmentation is further complicated by the temporal variability in traffic. What little scientific results are available are based on vehicles per day. The typical hourly distribution of traffic on the road near the Oyu Tolgoi Mine is shown in Figure 9. Although traffic on this road is currently around 200 vehicles per day, the distribution is fairly typical for a roadway where there is a time period in late evening and early morning with almost no traffic. Even when traffic reaches a level of concern at thousands of vehicles per day, there is commonly a six hour period (or more) during which there are only a few vehicles per hour.

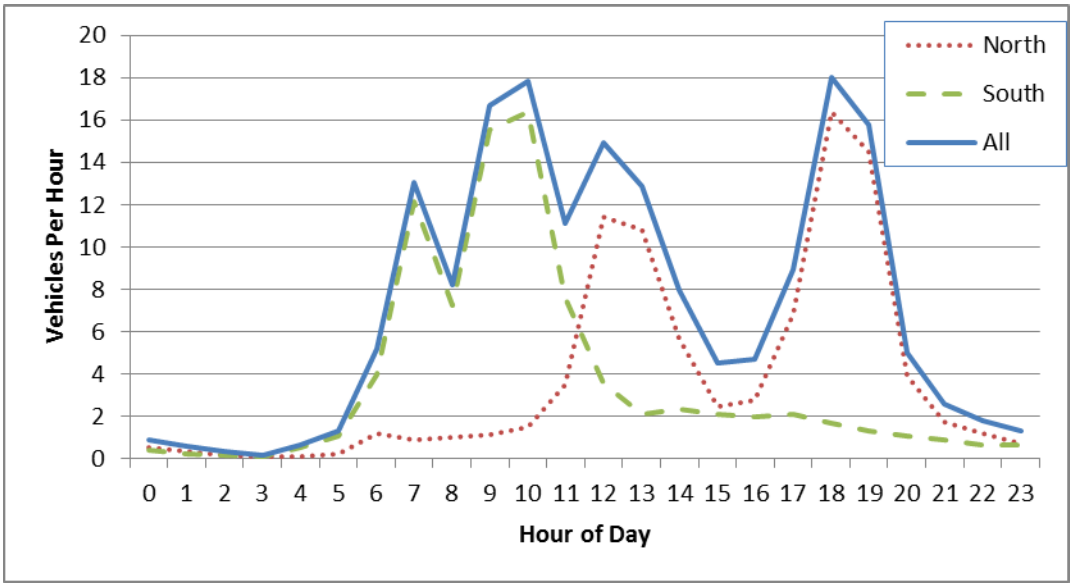

Figure 9: Average Daily Traffic Distribution on Oyu Tolgoi Road (Unpublished Data Provided by Oyu Tolgoi Mine Dec. 2014 – June 2015)

Seasonal differences are less variable, but still should be considered. Figure 10 shows a roadway in North America where the monthly average traffic in July and August is twice the annual average. This is of particular importance because the species of concern is Grizzly Bear (Ursus arctos horribilis), which are more active in the summer months.

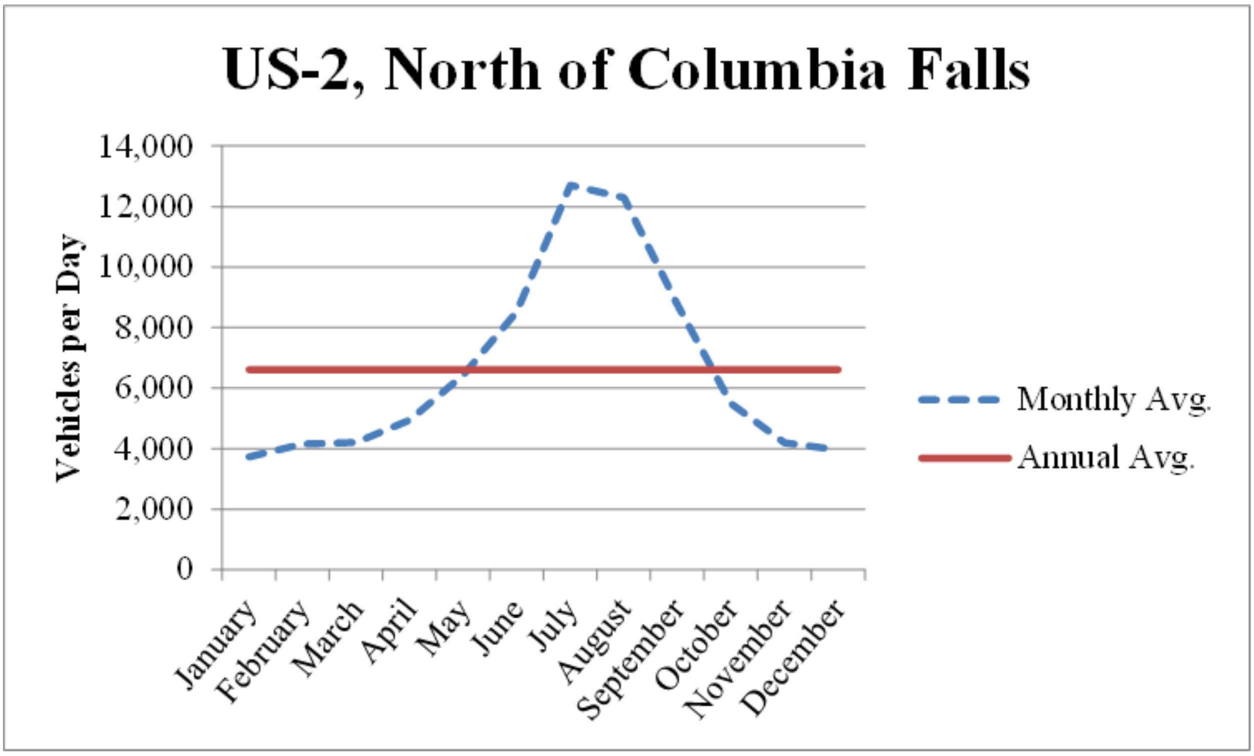

Figure 10: Extreme Example of Seasonal Traffic Variation in North America

Anecdotally, the truck traffic in the Gobi desert does not appear to have a heavy seasonal variation. Continued study is needed to determine what traffic thresholds create a significant barrier and warrant mitigation.

2.4. Mortality Due to Animal-Vehicle Collisions

To put a finer point on the relationship between traffic and habitat fragmentation, the barrier effect can be due to animals avoiding the road and animals that attempt to cross, but are killed by collisions with vehicles. Thus the barrier effect is the addition of repelled crossings and killed animals attempting to cross (Figure 11).

Figure 11: Relationship Between Traffic and Animals Wanting to Cross Roadways

When considering road mortality as traffic increases, the good news is that typically when traffic reaches a certain point, road mortality will decline. The bad news is that this decline is due to a decrease in animals attempting to cross, and heavy habitat fragmentation. Figure 12 shows the estimated wildlife mortality curve for a study of white tailed deer (Odocoileus virginianus) in North America and another study of moose (Alces alces) in Sweden.

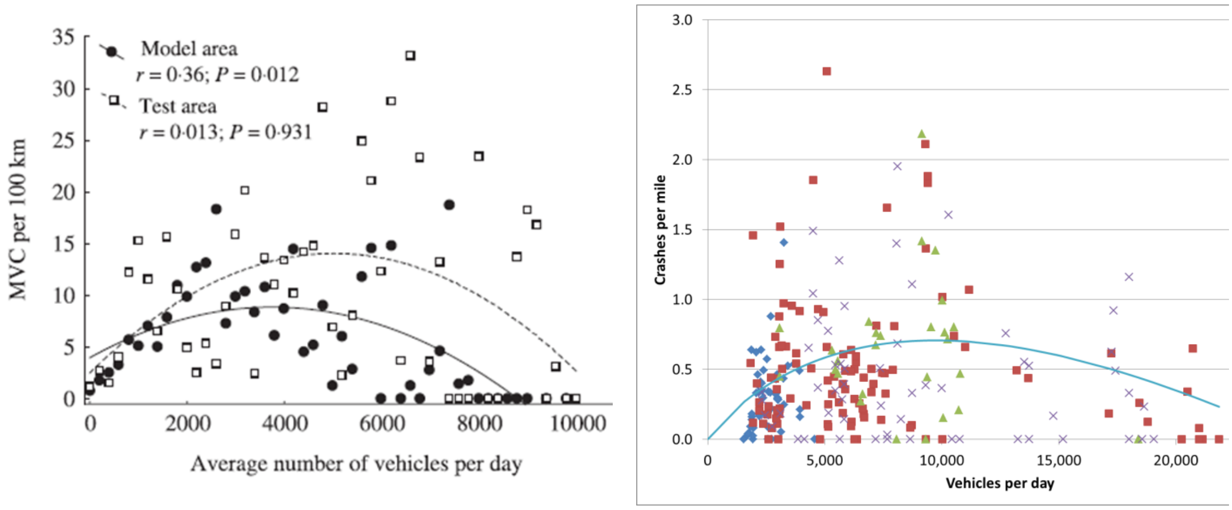

Figure 12: Average Animal Vehicle Collisions for Road Segments of Different Traffic Intensity. Left: Moose in Sweden (Seiler, 2005); Right White-tailed Deer in North America (Dezort and McGowen, 2010)

If there were significant road mortality in the Gobi Desert due to roads and railroads, carcasses near the roads and rails would likely be noticed. Certainly carcasses along railroads have been documented, but these are almost entirely due to fence entanglements (Personal Communications Badamjav Lkhagvasuren, Mongolian Academies of Science, 2015). Oyu Tolgoi Mine has made a commitment to investigate wildlife mortality, but staff members report that the animal mortality found is almost entirely within the lease area and not near the road (Personal Communication, Dennis Hosack, Oyu Tolgoi Mine 2015). The Ministry of Transportation does not track vehicle collisions outside of a few major populated areas.

2.5. Habitat Degradation Adjacent to the Roadway/Railway

Lower likelihood of presence of animals, or total avoidance for some distance adjacent to roadways has been noted for similar species:

- Tibetan antelope (Pantholops hodgsoni), Tibetan gazelle (Procapra picticaudata) and Kiang (Equus kiang) all had significantly lower densities within 500 m of the Qinghai-Tibetan highway than areas further away (Yin et al. 2007).
- Wild yak (Bos grunniens) avoidance distances were estimated at 999 m ± 304 m. (Lian et al. 2012).
- Kiang avoidance distance estimated at 568 m ± 83 m (Lian et al. 2012).
- Tibetan antelope avoidance distance estimated at 286 m ± 27 m (Lian et al. 2012).
- Tibetan gazelle avoidance distance estimated at 177 m ± 14 m (Lian et al. 2012).
- Bighorn sheep (Ovis canadensis) in North America avoid roads and traffic for a distance of 350-500 m (Papouchis et al. 2001).

For nomadic and migratory ungulate species in the Gobi, avoidance distance has been conservatively estimated to be up to 5 km from the road (ESIA 2013). Huijser et al. (2013) indicate that when wildlife crossing structures are built, traffic should be blocked from view of wildlife for a distance of "perhaps 200-300 m for gazelle species, 300-500 m for argali sheep, and 500-600 m for khulan."

Studies with actual wildlife presence data are needed. These distances appear to be largely based on anecdotal observations of animal avoidance of vehicles in the open desert. There also appears to be anecdotal evidence that khulan may adapt to regular traffic on a paved road. During the development of this report, the author witnessed three khulan near the UK-GS Road (Figure 13). There were at least a few trucks that passed this location several minutes before. When the khulan were seen, they were generally foraging. It was not until our vehicle stopped to view them that they began to run.

Figure 13: Khulan Seen within 100m of UK-GS Road

2.6. Increased Human Access

A secondary wildlife impact of roads is that they make it easier for humans to access wildlife habitat. Roads can lead to increased land development, and increased human activities such as hiking, viewing wildlife and hunting. Poaching is a major concern in the Gobi. Although not a direct cause of the road, better access to certain areas of the Gobi might increase the poaching/hunting for wildlife. Lkhagvasuren (2012) noted hunting of Mongolian Gazelle increased more in areas with a growing number of mining extraction sites. Aside from the population growth in and around new mining developments, the population in the Omnogovi and Dornogovi aimags is relatively flat or declining. Since transportation infrastructure is a result of mining development (and not the other way around), the most likely impact of increased human access is poaching.

2.7. Road Dust from Traffic on Unpaved Roads (5)

Road dust has a negative impact on vegetation adjacent to the roadway, which can degrade wildlife habitat. Compared to the habitat fragmentation of the traffic itself, the road dust probably has little additional impact on habitat loss or habitat fragmentation.

Road dust has been identified as a health concern for black-tailed gazelle. Jackson (2015) summarizes findings of dust having negative health impacts on people and wildlife in the area.

Although not a major wildlife impact, at the request of the sponsor, extra road dust mitigation information is included in this report primarily due to their impact on human health, aesthetics, road stability, and the sustainable use of road construction material. Best practices for mitigating road dust are provided as a separate chapter after the mitigations chapter.

3. CURRENT TRANSPORTATION SYSTEM

3.1. Existing Infrastructure

The primary transportation infrastructure of concern in the south Gobi desert consists of two asphalt paved roads and one rail line. There are also several spur roads, unimproved roads and roads of less concern.

For clarity, road surfaces will be classified as paved, gravel and unimproved.

- A paved road has an asphalt concrete pavement surface.
- Gravel roads have an improved surface using gravel with good structural properties from a gravel pit or crushing plant. The road can be geometrically shaped to have a crown and ditches for water drainage. The gravel surface could also include one or more of the treatments discussed in chapter 5. Sometimes roads with a gravel surface are referred to as being “paved” with gravel, but are not called paved roads in this report so as not to be confused with roads paved with asphalt concrete pavement.
- Unimproved roads are travel corridors where vehicles have driven over the natural ground. Even though vehicle traffic may have removed vegetation and compacted natural soil to give the appearance of a road, no improvements have been made.

Recently two paved roads were constructed in the Gobi to connect mines with China for hauling mining products. These roads include:

- A 107 kilometer (km) road from the Oyu Tolgoi mine site to the Gashuun-Sukhait border crossing (OT-GS Road).
- A 245 km road from the Ukhaa Khudag mine to the Gashuun-Sukhait (UK-GS Road, formerly known as the Energy Resources Road).

The last 16 km of the OT-GS Road are in, adjacent to, or close to the Small Gobi B strictly protected area (Small Gobi B SPA). Along this segment the UK-GS road comes very close to the OT-GS road.

There is only one existing rail line in the Gobi Desert. Much further east from the two mining roads mentioned above is the Trans-Mongolian railroad that heads generally south-south-east from Ulaanbaatar to the border crossing at Zamin-Uud.

There are also several spur roads (gravel and paved) built to connect mines to airports, nearby towns and to the paved roads mentioned above. One example is:

- A 39 km road connecting Oyu Tolgoi mine site to Khanbogd (OT-KB Road)

Some paved roads connect aimag centers with Ulaanbaatar, but do not continue into the south part of the Gobi Desert. For example a paved road connects Ulaanbaatar with Dalanzadgad.

The flat dry landscape allows for off-road vehicle travel for freight and passenger trips, which is common. The off-road travel will often consolidate into a single track or set of tracks resulting in a road that has regular traffic but is not improved with either asphalt pavement or gravel. According to Keshmat et al (2013), when no improved roads exist there is often not a single track but bunched parallel tracks that can create a travel corridor that is 30-125m wide, but can be as wide as 900m.

3.2. Planned Infrastructure

There are plans by the Ministry of Transportation to construct two additional paved roads in the south Gobi Desert. One will generally parallel the Trans-Mongolian Railway. Another is further west from the recent mining developments, running generally north-south to cross the border at Shivee Khuren.

There are plans for an east-west railroad from Shivee Khuren to Dalanzadgad to ZuunBayan, where it will cross the Trans-Mongolian Railroad and continue east to Choibalsan. There are plans for a north-south railroad that would generally follow the UK-GS Road, which is partially constructed.

These infrastructure projects are planned in phases and could be many years from construction.

3.3. Animal Vehicle Crash Histories

The Mongolian Ministry of Transportation does not have any standard tracking system for vehicle collisions except in a few of the more populated cities that have more traffic accidents (for example, Ulaanbaatar, Nalaikh, and Zamiin Uud) (Personal Communication Dr.Gerelnyam, Ministry of Road and Transportation).

OT staff respond to reports of injured wildlife, but events are almost entirely within the mine site lease area (Personal Communication Dennis Hosack, 2015).

3.4. Current Traffic

Several sources were consolidated to identify traffic flows on roads in the south Gobi desert. Traffic flows identified in literature are summarized in the text below. Raw count data gathered from a variety of sources are shown in Figure 14, and described further below.

Several times a year, the Ministry of Transportation counts vehicles at various locations around the country. These counts are published in a report (Ministry of Transportation, 2014). These are two-day counts collected by hand. Because there are often several unimproved roads that may connect two nearby towns, it is not always possible to identify the exact road where data was collected. Those in the Omnogovi and Dornogovi aimags are shown in black in Figure 14. Unimproved roads south of Sanshand had 660 and 720 vehicles per day. The unimproved road west of TT had 490 vehicles per day and the road north of TT had 280 vehicles per day. The road south of TT (assumed to be the UK-GS Road) had 540 vehicles per day.

In addition to the 540 vehicles per day, other traffic counts were found for the UK-GS Road. Because this is a road of concern, several numbers were reported in the literature.

- 2000 trucks a day was reported in a news article quoting a politician (Watts, 2011).
- 500 trucks a day was reported by ER (McGrath et al., 2011).
- Toll booth data was provided by the Gashuun Sukait Road Company. Tolls collected per day ranged from 500 to 3500 (shown in gray in Figure 14).

In 2011, the traffic volume on the OT-GS Road was reported as 388 per day and projected to increase to over 1600 by 2030 (TBC and FFI 2011). Current traffic is around 200 vehicles per day (Unpublished data provided by Oyu Tolgoi Mine, 2015, shown in red in Figure 14).

On September 1-2, 2015 traffic counters were placed on the gravel road heading east toward Khanbogd. This two day count showed an average of 140 vehicles per day (shown in blue in Figure 14).

Finally, the railroad (green in Figure 14) has an estimated capacity of 20 trains each direction (Bullpin 2008). The capacity is limited because the railroad uses a single track and the spacing of couplets to allow northbound and southbound trains to pass each other.

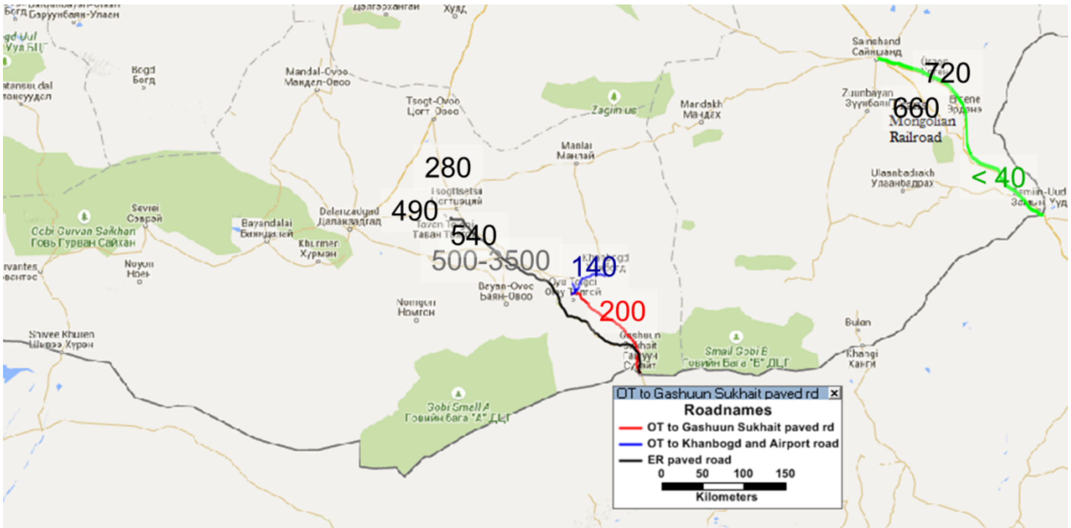

Figure 14: Current Traffic in Vehicles per Day. Sources: Black = Ministry of Transportation, (2014), Gray = GS Road LLC (unpublished data 2015), Blue = McGowen (unpublished data 2015), Red = Oyu Tolgoi (unpublished data 2015), Green (Bullpin, 2011)

As mentioned previously (Figure 9), daily distributions of traffic typically are higher from 7am to 7pm with very low traffic in the late evening and early morning hours.

3.5. Traffic Demand

In order to predict future traffic, it is helpful to understand what causes demand for traffic and estimate how that might grow in the future. Personal travel between towns is one source of traffic. A larger source of traffic is trucks shipping ore to be processed in China.

3.5.1. Personal Travel

According to the 2010 census, the two aimags that contain most of the South Gobi Desert are sparsely populated:

- Omnogovi: 60,855 people at 0.4 people per square km
    - Of which 18,781 are in aimag center
- Dornogovi: 57,930 at 0.5 people per square km.
    - Of which 33,932 are in aimag center

The population growth is centered around mining sites, and to a lesser extent in soums connected to China border crossings. Otherwise the population is relatively static. Primary population growth is in:

- Tsogttsetsii near the UK mine, which increased from a population of 2,200 in 2008 to 10,000 (including temporary workers) in 2011. (McGrath et al., 2011)
- OT has 15,000 employees, many housed at the mine site (McGrath et al., 2011)
    - Khanbogd near the OT Mine has 9000 residents (McGrath et al., 2011)

With low auto ownership the population growth has a small impact compared to freight movements.

3.5.2. Freight Demand

Looking at the potential demand and potential production capacity for mining products may provide insight into the future freight traffic on roads in the South Gobi.

For pavement preservation, the GS Road Company only allows 70 ton trucks on the UK-GS Road. Anecdotal reports of trucks with nearly twice that load have been reported traveling on unimproved roads. A very rough estimate would be every million tons of ore extracted per year would result in an average of 40 trucks per day.

Prior to the global recession, freight traffic was increasing significantly and the increase was expected to continue. In more recent years, there has been a decrease in the demand for coal and other resources by China. Anecdotally, the traffic seen in the 2015 site visit was much lower than that seen during the author's previous visit in 2013.

There are 12 billion tons of proven coal reserves in Mongolia. China's coal industry estimated to absorb 20 million tons of coking coal imports annually for the next 5-10 years (McGrath et al. 2011).

The Ukhaa Khudag (UK) coal mine is owned by Energy Resources LLC and at Tavan Tolgoi. They mined 3.8 million tons in 2010 with plans to expand to 15 million tons (http://www.energyresources.mn/news/show/id/6). The Ukhaa Khudag Environmental and Social Management Plan states that the Tavan Tologoi coal reserve could supply 30 million tons a year for 30 years (Ukhaa Khudag, 2015).

Note there is at least one other mine near the UK mine not owned by Energy Resources LLC that is referred to as the Tavan Tolgoi (TT) mine. These mines seem to be occasionally combined in the literature. Walton (2010) identifies a small TT mine operated by the aimag and Qinhua that is producing 1 million tons per year and likely to continue at that rate.

The Oyu Tolgoi (OT) copper mine has an expected output of 450,000 tons a year (Watts 2011). Lkhagvasuren et al. (2011) estimated mine production at a million tons per year. Note that the OT mine is currently running about 100 trucks per day based on their traffic counter (200 counting both directions), which indicates a slightly higher output. Johnston (2011) states that the OT mine will be capable of more than 100,000 tons per day, which could be 36.5 million tons per year if continuously operated.

Lkhagvasuren et al. (2011) identifies several other mines; some are further west and would not use the same travel corridor as the mines mentioned above. They consolidated other sources for estimated production in the near future:

- Nariin Sukhait, a coal mine with potential production of 2 million tons,
- Ovoot Tolgoi, a coal mine with potential production of 10 million tons,
- Baruun Naran, a coal mine with potential production of 6 million tons,

- Tsagaan Tolgoi, a coal mine with potential production of 2 million tons,
- Tsagaan Suvaga a copper mine with potential production of 0.15 million tons, and
- Sumber, a coal mine with potential production of 5 million tons.

The numbers above could be combined to approximately 50 million tons and 2,000 trucks. Rail transport is expected to decrease the shipping cost of coal and make it more competitive with sources from other countries. Walton (2010) indicates that if truck traffic rose to exceed 2,000 it would be more economical to ship by rail and a rail-line would be built. Some of the higher freight estimates above assume availability of rail as a shipping option, which lowers cost enough to keep demand high.

4. MITIGATIONS

With these issues, the following mitigations are suggested as tools to be considered when addressing wildlife impacts of transportation infrastructure.

4.1. Adaptive Management and Data Collection

Specific mitigations discussed below are based on the current best knowledge of the challenges documented in previous chapters. However, many questions remain that if answered, would improve guidance for these mitigations. Further, predicting future changes in the Gobi is difficult. An adaptive management approach is strongly encouraged in order to incorporate new information and improved understanding of the challenges, which will allow the improvement of mitigation guidance as things change in the future.

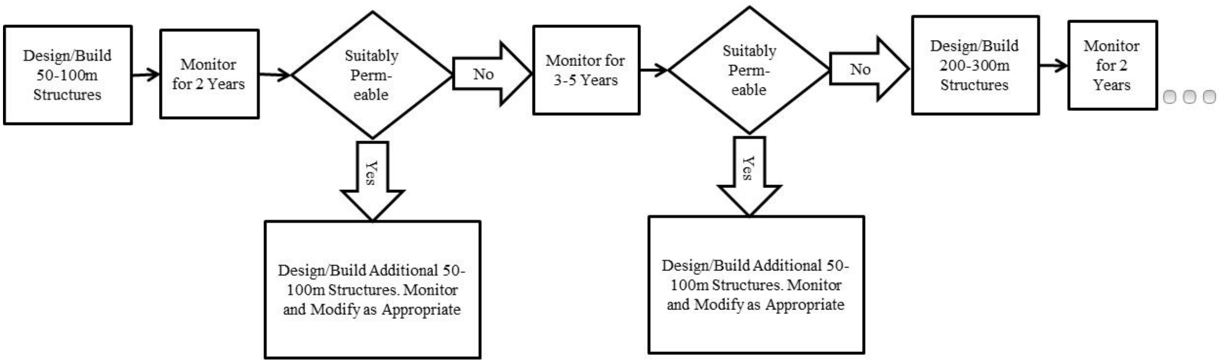

Figure 15: Example of Adaptive Management Process (Huijser et al. 2013).

Data and research needs discussed in this section that will inform an adaptive management approach include:

- Traffic flow data,
- Wildlife mortality data,
- Wildlife movement data and research, and
- Mitigation monitoring.

Traffic data reported in Section 3.4 was collected by a variety of organizations for a variety of reasons. It would be beneficial to compile this data and provide it to researchers and organizations working on habitat fragmentation. Additionally, the Ministry of Transportation should be encouraged to install permanent counters on existing and planned paved roads in the Gobi Desert. The permanent counter installed by the Oyu Tolgoi mine is a sound detector and could be used elsewhere. This type of counter is called an inductive loop, which is a loop of wire buried under pavement. These wires are very inexpensive to install when the road is built, but have to be cut into the pavement after the road is built. There are four loops in the pavement, and, two in each lane. If a speed measurement is not needed, one loop installed in each lane can provide a count. In Figure 16, a black line is drawn over one of the loops in the image to make it more visible. For further information on this technology, contact Dashnyam Batsuuri with Oyu Tolgoi Mines.

Figure 16: Induction Loop Traffic Counter on OT-GS Road (one loop darkened)

As discussed in Section 3.4, not much data exists on wildlife vehicle collisions. This data is important in order to determine the magnitude and location of this challenge. Additionally, this data can help with understanding of other wildlife movement questions, and prioritization of mitigation locations.

Considering the anecdotal information indicating that mortality from vehicle collisions is minimal, it may not warrant a costly monitoring program. However, a repository can be developed at a very low cost. Two examples are

- www.srazenazver.cz in the Czech Republic, and
- http://mapserv.utah.gov/wvc/desktop/dataentry.php in state of Utah, USA.

These programs allow researchers, public employees, private employees and the driving public to report wildlife vehicle collisions and carcasses seen in roadsides by webpage, smartphone application, or paper. Having a standard reporting form and central repository increases the number of reports submitted and documented

There are several important questions on wildlife movement and behavior that need more clarity. A better understanding can lead to improved mitigation management. Important research questions include the following:

- How much traffic on a roadway or railroad creates a significant barrier for various species?
- What is the width of habitat degradation adjacent to the road for various species?
- Do cut and fill slopes on railroads create a barrier to wildlife?
- Where are priority wildlife corridor movements for various species?

To a certain extent the corridor movements question has been answered. For khulan and gazelle, there are nomadic movements with no clear priority corridors. However, continued study may provide some guidance on priority corridors such as connecting key water sources. Continued efforts on collecting collar data and related research studies are needed.

Lastly, there is a need for monitoring and research on mitigation effectiveness. For any mitigations implemented, a monitoring program should be implemented in order to evaluate the effectiveness and improve future design. The most important type of mitigation to monitor is wildlife crossing structures. Figure 17 shows a test site with three monitoring methods. A trail camera is used to take a picture when an animal moving through the area is detected. A sand tracking bed is installed. A researcher can count the number of tracks and rake out the sand at regular intervals. A string of barbed wire creates a hair snag for genetic sampling.

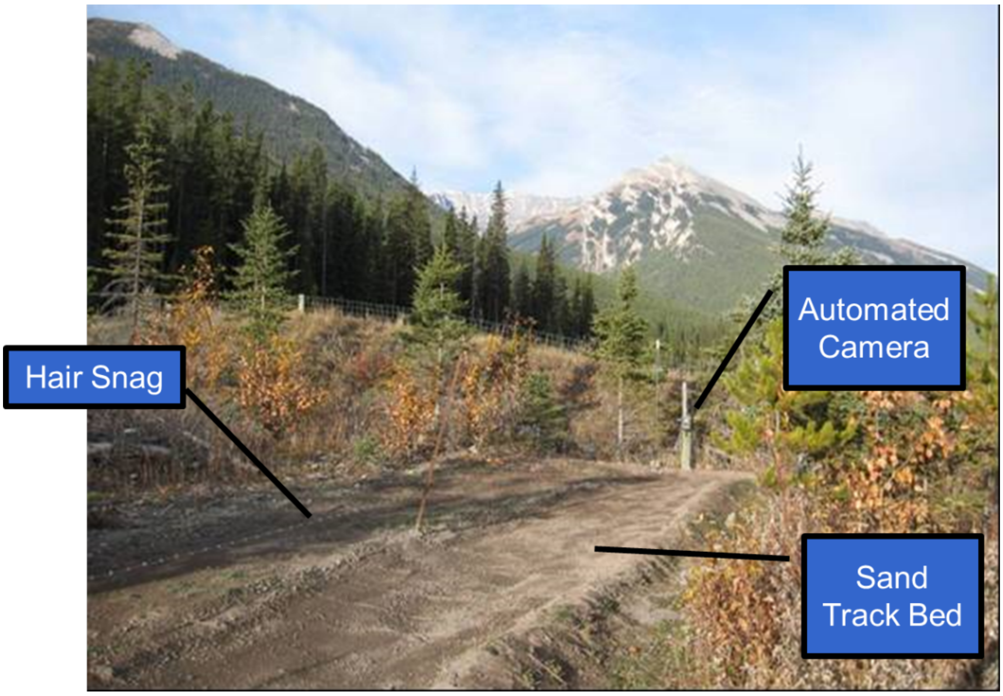

Figure 17: Monitoring Effort on Wildlife Crossing Structure

4.2. Road Locations

Mitigation costs are reduced when wildlife considerations are incorporated early in the planning process before the road is built. An alignment that has the least impact on wildlife can be found by seeking advice from experts on the species of concern. Finding a road alignment that has the least impact on wildlife is challenging in the Gobi Desert because of species that move nomadically and the desire to ship mining products to China. If a road connects a mine to China, it will have to bisect the habitat.

4.3. Managing Demand

Continued efforts to limit human developments by designating protected areas will reduce the number of possible developments that result in traffic. This will not solve the problem completely, because a single mine may be able to create enough freight truck traffic to create a barrier to wildlife.

Even if the economic forces result in the same demand for mining resources, there are ways to meet the demand with less resulting traffic. Shipping coal by railroad instead of trucks means that one train could replace 100 trucks. One train is far less of a barrier than 100 trucks.

Another option provides an alternative to shipping coal by truck in order to be burned in a power-plant in China. Instead, a power-plant could be built at the mining site and the electricity sent to the destination by power lines. The UK mine investigated building a coal washing plant at the mine site. By washing the coal before shipping, the same energy potential can be shipped with 30 percent less weight. Thus the same energy demand can be met with 30percent fewer trucks (Ukhaa Khudag, 2015).

There are reports of plans for a copper smelter near the OT mine site or near Sainshand (Johnston, 2011), which would similarly reduce the concentrated ore to copper and reduce the freight tonnage for the same amount of copper.

4.4. Driver Awareness and Public Educations.

Public education on wildlife impacts of roads is important to build broad support for the program and find specific help. Some important elements of a public education program are detailed below.

The nomadic herding lifestyle provides a close connection with nature. Most Mongolians are either herders or have family relatives with a herding background within a couple generations. Building on this connection, making the case for the **need for conservation** among citizens is important in order to build broad support for a conservation program. Public opinion can help or hinder road mitigation efforts. A wildlife crossing structure could be considered as either a waste of resources or a critical victory for saving a species depending on general public perception of the habitat conservation.

There are several examples of existing public outreach efforts in Mongolia. Figure 18 shows a screen shot of a video created by the Wildlife Conservation Society that addresses the problem of wildlife impacts of roads and the need for mitigation.

Figure 18: Title Screen-shot of Video Prepared by Wildlife Conservation Society and produced by 95 Group.

In another example, there is a statue in Ulaanbaatar of an Argali. The plaque discusses the threat to wildlife of mining and road development (Figure 19).

Plaque Text:

King of the Altai

Mongolia is home to two sub-species of the mighty Altai giant wild mountain sheep. The Gobi Argali (Ovus Ammom Darwini) inhabits the Gobi Desert region. While the larges Altai (Altay) Argali (Ovus Ammom Ammom) is found in the [may be text missing here] Argali are truly nature's valuable gift to the people of Mongolia. But lately Mongolia's Argali population has been greatly disturbed by human livestock and mining industry encroachment into its traditional habitat. Argalis have been forced to travel long distances in search of more welcoming habitats and places safe from poachers. Under the initiative of Ambassador Galsangiin Batsukh, this piece of fine art was made by Canadian wildlife artist Rick Taylor and donated to the City of Ulaanbaatar.

Figure 19: Statue of Argali in Ulaanbaatar

Warning drivers of animal presence on or near the road is important. This may make drivers more attentive and more likely to avoid a collision if animals cross in front of vehicles. Because collisions may not be an issue, more important driver behavior might be to encourage vehicles to **"stay on the road,"** in particular to discourage chasing wildlife. Animals may habituate to moving traffic, but will likely flee if vehicles stop and people get out of the vehicle to view wildlife. It may be difficult to stop this behavior due to the desire to view wildlife. However, encouraging motorists **not to stop the vehicle**, and particularly to **stay in the vehicle** when near wildlife might also be important messages.

It should be noted that many truck drivers are Chinese. Informative road signs (e.g., Figure 20) should include messages in the Chinese language.

Figure 20: Existing Road Sign on UK-GS Road

Mitigations that require driver compliance (such as **time of day restrictions and wildlife reporting** discussed below) could also be part of a public outreach effort.

4.5. Time of Day Restrictions

Restricting traffic on a road during certain times of the day may be beneficial. Khulan may be most active between 16:00 and 20:00 (ESIA 2013). Restricting traffic during this time will have a major impact on mine and truck company operations. It may be more effective to match a potential "curfew" with existing times of low traffic such as 24:00 to 5:00 (Figure 21). This could be limited to seasons of the year or certain weather events when wildlife are most likely to move across the roadway. For example in the state of Delaware (USA), the River Road in the Water Gap National Recreation Area is closed in March and April from 6 p.m. to- 6 a.m. when there is a forecast calling for rain with temperatures greater than 10º C. This allows multiple amphibian species to cross the road during their seasonal migration (Delaware Water Gap National Recreation Area, 2003).

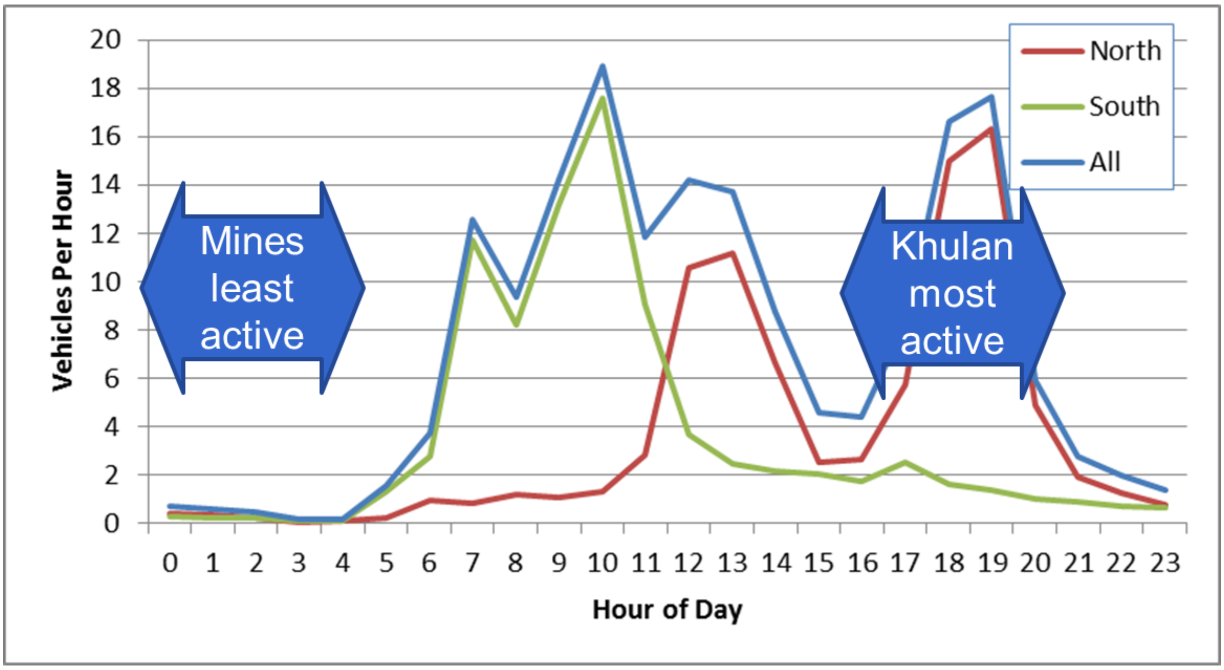

Figure 21: Existing Traffic on OT-GS Road with Potential Times for Traffic Restrictions

The restriction could be mandatory or voluntary. This solution could be as simple as signs on the road that say "For wildlife protection, travel on this road is restricted from 12am to 6am, emergency travel only."

4.6. Wildlife Crossing Structures

Wildlife crossing structures allow a separated path for wildlife to travel over or under the roadway. This section provides a summary of some of the more crucial design decisions relating to wildlife crossing structures. For more detail about designing wildlife crossing structures refer to Huijser (2008), Huijser et al. (2013), Clevenger and Huijser (2011) and Iuell (2003).

Based on khulan and gazelle behavior, recommendations on certain design elements of wildlife crossing structures have been suggested.

- An average one-day walk of a collared khulan that was tracked as it followed a fence barrier along the Trans-Mongolian Railroad was found to be 12 km (Kaczensky et al. 2011). Thus a maximum spacing of 12 km between crossing structures is recommended.
- There is not one exact structure size that is always best. With multiple species, it is common to have a mix of structures, such as placing several small structures in between each large structure. Some recommended structure sizes include:
  - The new standard for Mongolia specifies several possible sizes of openings for crossing structures focused on large animals:
    - 70 m overpass
    - 40-50 m overpass
    - 10 m overpass
    - 2.5 m high by 5 m wide up to 4 m by 7 m and no minimum size.

  - The railroad being constructed by the Mongolian Railroad Company paralleling the UK-GS Road has box culverts that are 4m by 4m as either a single or double box culvert (Figure 22).
  - Based on the net-positive impact, Huijser et al. (2013) recommended a combination of large structures, both underpasses and overpasses of three sizes. Underpasses should be 5-7m high.
    - 500-1,000 m wide
    - 200-300 m wide
    - 50-100 m wide
- There has not been a definitive stance on whether animals will go over the road or under the road. Generally, it is accepted that an overpass would be better for ungulates (Clevenger and Huijser, 2011). Due to high summer temperatures in the Gobi, it is possible that livestock will use underpasses for shade. The regular presence of livestock could render underpasses ineffective for wildlife.
- An underpass with a level travel path, where the animal can see through the structure for some distance, may be preferable to an overpass that goes up and over the road and prevents the animal from seeing across. Because of the avoidance behavior, and open space, it is expected that a level travel path for the animal where the animal can see through the structure (or across the top of the structure) is important for usability.
- Also, because of the vehicle avoidance behavior, sound and visual barriers have been recommended. Huisjer et al. (2013) recommended extending the visual barrier along the road for 200-600 meters. This visual barrier can also act as a fence to funnel animals to the structure. It is not desirable to extend fencing beyond this distance because the fencing will become a barrier.

Most of these recommendations are based on use by other species in other areas of the world, or based on assumptions of use due to khulan and gazelle behavior. The fact is, we don't know what the usage will be for different types and sizes of structures for khulan and gazelle in the South Gobi until wildlife structures are built and monitored. Generally larger structures are more effective, but more costly. A better understanding of which types and sizes of structures are best will have to come with time as different structures are attempted and studied. As discussed previously, an adaptive management approach is preferred.

Figure 22: Double Box Culvert along Partially Constructed Railroad

One challenge in the Gobi is that several different entities will build a linear transportation infrastructure that run parallel to each other. One entity may not be willing to provide mitigation because it does not want to invest resources to make its road or railroad permeable only to have the adjacent facility become a barrier. There is a need to designate priority travel corridor for wildlife, and plan nearby infrastructure accordingly, so that a single linear infrastructure will not become a barrier. For example, crossing structures could be considered on the UK-GS Road and the OT-GS Road at the same latitude as the existing partially constructed railroad structures, particularly the one shown in Figure 23.

Figure 23: Wildlife Underpass on Partially Constructed Railroad

Other locations of the partially constructed railroad may have limited functionality. Figure 24 shows constructed piers with an estimation of the beam and railroad structure on top shown with a black bar. Notice the height of this structure allows very little sight through the structure and from a distance may look like a barrier.

Figure 24: Partially Constructed Railroad Bridge Showing Potential Structure Size in Black

Generally overpasses can be slightly more expensive than underpasses. Also, lowering the road for overpasses so that the animal path over the structure remains level will also increase the cost. Considering the water table in the Gobi, a lowered road could require pumping to keep the roadway dry.

Generally, costs of crossing structures are US$20,000 to $50,000 per meter of width (note the exchange rate at the time of this publication is about 2,000 Tugrik to US$1). Overpass widths over 50 m may require additional lighting, fire suppression and ventilation for the vehicle traffic, which increases the cost. For overpasses over 50m in width the cost may range from $50,000 to $200,000 per meter (Huijser et al. 2013).

4.7. Truck Platoons

Traffic could be held on the road at key locations in order to create a platoon of trucks that would result in large gaps with no traffic. Consider a time of day when the traffic flow is 30 vehicles per hour. On average the gap between vehicles will be 2 minutes. Some gaps will be larger or shorter. A typical gap distribution (Poisson model is often assumed for low flow two-lane roads) at 30 vehicles per hour means that the probability of a gap being larger than 10 minutes has a likelihood of less than 1 percent. If these same 30 vehicles were stopped until 10 at a time queued up and then were released as a platoon, there would be three platoons per hour where vehicles within the platoon would all be a few seconds apart. The gap between each platoon would be nearly 20 minutes (Figure 25).

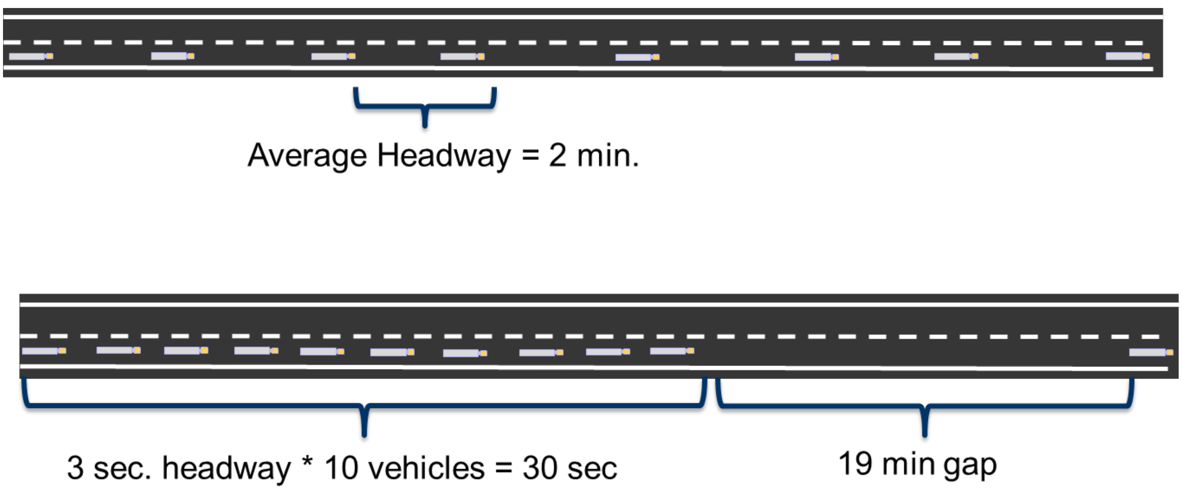

Figure 25: Conceptual Example of Truck Platooning (not to scale)

Considering two-way traffic with similar platoons, gaps could be half the size at any given point. A larger gap could be created if it was justified based on new wildlife behavior data as it becomes available. This mitigation could be limited to certain seasons or times of day when wildlife are most active.

4.8. Fencing

Because fencing along the Trans-Mongolian Railroad has proven to be a near total barrier, use of any fencing on new roads and railroads should be highly discouraged. If fencing is used, refer to road fencing standards (Mongolian Agency of Standardization and Meteorology, 2014).

4.9. Restricting Off-Road Traffic

Particularly for the UK-GS Road, there has been historic off-road traffic running parallel to the paved road. This causes dust and widens the footprint of impact for this travel corridor. The benefits to the driver of traveling off-road as opposed to on the paved road are higher weight allowance and avoidance of tolls. The GS Road Company only allows 70 ton trucks in order to manage damage to the pavement. A truck may be able to carry twice this much, making the trip more profitable if it travels off-road. The toll is about 1,000 Tugrik so this a minor cost compared to fuel, time and vehicle wear. Note the truck would pass eight toll booths for a round trip, but still tolls are a minor cost compared to fuel, travel time and wear on the vehicle. The real benefit to driving off-road is the ability to carry a larger load.

The GS Road Company has curtailed off road traffic in two ways. First, the company has built earth berms adjacent to the road to make it difficult for vehicles to exit the roadway (Figure 26). Second, personnel patrol and charge off-road vehicles. The GS Road Company has the authority and staff to identify off-road vehicles and charge them with the toll. Another challenge is that because the GS Road Company patrol staff is private and not official law enforcement, some drivers question their authority. Creating a steeper fine for off-road traffic and giving the GS Road Company the authority to enforce this fine would further limit off-road traffic.

Figure 26: Berms Restricting Off-Road Traffic. Left is a single short berm blocking an existing entrance/exit point of road. Right shows a continuous berm paralleling roadway.

Anecdotally, traffic paralleling the UK-GS Road was not seen during the 2015 visit. Discussions with locals and GR Road Company staff confirm this. Off-road travel may no longer be an issue. If the demand for mining products by China increases and traffic increases, off-road traffic could return. If so, either fines or earth berms should be used to limit it.

5. MANAGING ROAD DUST

As discussed in Section 2.7, road dust can have a negative impact on human health, animal health, and vegetation health near the roadway. The loss of fines in the form of dust also contributes to distresses such as washboarding and to accelerated gravel loss from the road surface (fines are defined as material passing the 0.075 mm sieve). At the request of the sponsor, extra focus was placed on managing road dust, thus this mitigation is provided in a separate chapter. This chapter provides a summary of best practices for managing road dust on unpaved roads.

Unpaved roads are sometimes the only economically feasible types of roads in rural areas and those with low traffic volume (Skorseth and Selim 2000). Low volume, unpaved roads serve as main arteries for mining, logging, and agricultural industries bringing goods to market (Keller and Sherar 2003). Roads used in transporting such goods experience heavy truck traffic and often require supplemental construction and maintenance activity in order to maintain user safety and a good driving surface. Good construction of the road base and surface layers and use of good quality materials is an important step in minimizing future maintenance activities on gravel roads (Skorseth and Selim 2000).

In the Gobi Desert many roads are little more than a dirt track carved through the local vegetation. In other geographic areas with different soil and rainfall conditions, these unimproved roads are often suitable only for very low volume traffic and light loads. As traffic increases, roadway improvements are considered in order to create a safe and passable driving surface. Such improvements include the addition of appropriate wearing course materials, shaping, and if warranted by traffic, the incorporation of a soil stabilizer and/or the addition of a surface treatment such as a dust suppressant or a bituminous seal coat. Anecdotally, the unimproved dirt-track roads in the Gobi have been able to withstand considerable amounts of truck traffic before enough rutting and other failure occurs to require any kind of maintenance. Given the arid conditions and structural properties of native soil in the Gobi, there may be opportunity for a more innovative approach to unpaved road construction and maintenance that takes advantage of these local conditions. However, a local calibration to the Gobi Desert of the typical best practices was beyond the scope of this study. This chapter includes best practices for unpaved roads in other parts of the world.

Often, low volume roads are very inexpensive to build, but can be costly to maintain. Designing with future maintenance in mind may increase upfront costs, but can result in cost-savings and reduced environmental impacts associated with frequent gravel replacement over the lifetime of the road (Lunsford and Mahoney 2001). Furthermore, many dust treatments also improve the durability and safety (smoother riding surface) of a road. Although this summary of best practices focuses on managing dust on unpaved roads, it does so in conjunction with considering pavement durability, drainage and road maintenance. This chapter:

- Provides guidance on testing and selecting materials for building gravel roads
- Summarizes road geometry issues
- Discusses common road failures and how to mitigate them
- Details how to use dust suppressants and stabilizers

5.1. Roadway Material

Proper selection of roadway material is critically important. Use of appropriate aggregate can result in a range of benefits such as reduced maintenance and reduced vehicle damage. Selecting an appropriate aggregate can also greatly reduce sediment loss from the roadway, in turn leading to reduced dust and reduced health and environmental impacts. However, in some areas, it may not be possible to acquire appropriate aggregate at an economically feasible cost. In such instances, locally available marginal aggregates can be used (Lunsford and Mahoney 2001, Jones, et al. 2013) provided that the expected performance is understood and appropriate measures are taken to ensure that an acceptable level of service can be maintained.

Roadway material should be selected so as to provide all weather passability (i.e., vehicles can drive road without getting stuck) for the type of traffic that uses the road. Roads carrying very light vehicle traffic will not require the same materials used on a heavy haul road servicing a mine. Unpaved roads typically consist of three layers; the natural ground or subgrade, the base layer placed on top of the subgrade, and the wearing surface on top of the base layer. Material used for the base of paved roads is suitable for use on unpaved roads, but is not suitable for use as a wearing course as it usually contains insufficient fines and plasticity to resist abrasion and displacement by traffic.

Selecting appropriate unpaved road materials is based on a few specific properties that greatly impact the quality:

- Gradation, or particle size and distribution
- Fines content
- Clay content
- Material shear strength

These qualities can be easily and cheaply evaluated through simple laboratory tests. Common tests used in the US have been specified by the American Association of State Highway and Transportation Officials (AASHTO), American Society for Testing Materials (ASTM) and various state departments of transportation (e.g., Caltrans and Texas):

- Gradation analysis using AASHTO T 27 or ASTM C136 standards.
- Plasticity test:
  - Atterberg Limits using AASHTO T 89 and T 90 or ASTM D4318 standards.
  - Bar linear shrinkage per Caltrans CT 228 or Texas Tex-107-E standards.
- Strength test such as California Bearing Ratio (CBR) per AASHTO T 193 or ASTM D1883 standards.

Material testing and analysis before constructing the road may have small upfront costs (in the range of US$500 - $2,000), but can greatly reduce costs over the lifetime of the roadway by reducing the need for gravel replacement and the frequency of maintenance (Lunsford & Mahoney, 2001; Guimmarra, 2009; Skorseth & Selim, 2000; Jones, et al., 2013). How the test results are used in material selection is discussed below.

There are a range of recommendations, guidelines, and specifications for unpaved road base and wearing course materials. Most need to be adapted to suit local conditions and material availability. Many chemical treatments can be used to overcome limitations in material properties. However, many road managers have difficulty in interpreting test results, especially with regard to understanding performance if a grading distribution and a single plasticity criterion cannot be met by an aggregate supplier or from gravel located onsite. The following three-step procedure, summarized from the Unpaved Road Dust Control and Stabilization Treatment Selection Guide by Jones (2013), can be used to interpret key test results, assess the applicability of local material specifications, and understand how unpaved roads will perform if a particular material is used. These steps can also be used to make a decision regarding material choice, road design specifications, and chemical treatment selection. This procedure is a guide and NOT a specification, nor is it intended to replace existing specifications. It may need to be refined for particular situations and calibrated for local conditions, specifically traffic and climate.

5.1.1. Step 1 – Test Result Analysis

Grading Analysis

In this recommended approach, five key sieve sizes from a standard laboratory grading analysis test are required for understanding material performance and selecting an appropriate chemical treatment. These are the 25 mm, 4.75 mm, 2.36 mm, 0.425 mm, and 0.075 mm sieves. The first three are used to check for an appropriate mix of coarse, intermediate, and fine particles using the following simple formula known as the grading coefficient (G_c):

- $G_c = ((P_{25\ mm} - P_{2.36\ mm}) \times P_{4.75\ mm}) / 100$
- Where P is percent of soil passing through a given sieve size

Although the grading coefficient is determined using material passing the 25 mm sieve, a maximum size of 40 mm to 45 mm is preferable in the base course to provide adequate all-weather passability. The use of large aggregates in the surface material will reduce ride quality, make it noisy to travel on, and cause problems for the maintenance motor-grader operator. The maximum aggregate size should not exceed one third of the thickness of the compacted layer.

The percentage material passing the 0.075 mm sieve is also a useful indicator of how an unpaved road will perform and can influence the decision of what dust suppressant or stabilizer treatment to use. High percentages of material (i.e., >20%) passing this sieve imply that the road will be dusty when dry and may become slippery when wet. Low percentages (i.e., <10%), imply that the road will washboard and require regular motor-grader maintenance. Many unpaved road wearing course specifications based on paved road base course specifications limit the fines content to about 5% in the mistaken belief that this will reduce dust. Determination of the percent passing the 0.075 mm sieve (usually done using a wet process as part of a standard grading analysis) is, however, not as simple as determining the percent passing the 2.36 mm sieve (which can be done dry if necessary when checking aggregates in the field). Consequently for understanding general performance, the 0.075 mm material is factored into the grading coefficient equation as part of the passing 2.36 mm sieve material. However, the percent passing the 0.075 mm sieve is still required for optimal chemical treatment selection.

During the grading analysis, the angularity of the aggregate should also be visually checked. Cubicle or angular material interlocks better than rounded material (e.g., uncrushed alluvial aggregates) and consequently rounded aggregate should be crushed to obtain at least two fracture faces to enhance interlocking and prevent raveling.

Clay Content

The percent passing the 0.425 mm sieve is used together with the bar linear shrinkage (BLS), or plasticity index (PI, determined from the Atterberg Limit tests if the BLS test cannot be undertaken), to optimize the clay content using the following formula known as the shrinkage product (S_p):

- S_p = BLS x $P_{0.425mm}$ if the bar linear shrinkage is used, or
- S_p = (PI x 0.5) x $P_{0.425mm}$ if plasticity index is used

Note that using the bar linear shrinkage to determine the shrinkage product is more accurate than using the plasticity index, especially for silty non-plastic or slightly plastic materials. These materials often have a plasticity index of zero, and consequently also a shrinkage product of zero if the formula is used with plasticity index results. However, these materials will usually have some measurable linear shrinkage [i.e., BLS > 1], thereby providing a non-zero number to work with to better estimate expected performance. Recommendations for dealing with these situations if the plasticity index is used are as follows:

- If the PI of the material is equal to or greater than one, use the actual PI value without modification.
- If the material is non-plastic (i.e., PI = 0) and the percent passing the 0.075 mm sieve is less than 20%, set the PI to zero in the shrinkage product equation.
- If the material is termed "slightly plastic" in the laboratory test results and the percent passing the 0.075 mm sieve is less than 20%, set the PI to 1 in the equation.
- If the material is termed "slightly plastic" and the percent passing the 0.075 mm sieve is more than 20%, set the PI to 2 in the equation.
- If the material is non-plastic and the percent passing the 0.075 mm sieve is more than 20%, set the PI to 1 in the equation.

Shear Strength

The California Bearing Ratio (CBR) performed on material in the laboratory is the most commonly used bearing capacity test for granular materials used in unpaved roads. No formulas are required to interpret the results from this test.

5.1.2. Step 2 – Test Result Interpretation

Optimal unpaved road performance will usually be achieved when the base and wearing course materials test results fall within the following guidelines (Jones, 2013):

- The grading coefficient is between 15 and 35. Although not directly measured in the grading coefficient formula, a fines content (material passing the 0.075 mm sieve) of between 12 and 20% is typically required to meet the grading coefficient requirements.
- The shrinkage product of the base material is between 0 and 50 and of the wearing course material is between 100 and 365 (or between 100 and 250 if dust is a major concern and no dust control treatment is planned). Depending on the fine material fraction (percent passing the 0.075 mm sieve), the lower limit can usually be relaxed for lower traffic volumes (e.g., if the fines content is between 12 and 20 percent, the shrinkage product can be relaxed to 50 and 75 for traffic volumes of 50 and 75 vehicles per day, respectively).Many unpaved road specifications are based on using the paved road base

course specifications limit or even exclude any clay content in the mistaken belief that this will also reduce dust.

- Assuming that the road has a quality base course with adequate CBR (25 to 45 depending on truck traffic), the soaked CBR of the wearing course should be above a minimum of 15 (determined at 95% of AASHTO T 180 or ASTM D1557 compaction). If the traffic is predominantly trucks and the road is in a high rainfall area or storms of high intensity are common, a higher soaked CBR may be desirable if passability problems are an issue. However, higher CBR materials tend to have low clay contents and consequently washboarding may be a problem. Therefore, a balance between CBR and shrinkage product needs to be determined for optimal performance for specific traffic type and volume scenarios. Experience has shown that material complying with the grading coefficient and shrinkage product limits discussed above will invariably have a soaked CBR strength (compacted to 95% of the laboratory determined maximum dry density [AASHTO T 180 or ASTM D1557]) in excess of about 20%

A simple chart plotting grading coefficient (x-axis) and shrinkage product (y-axis) along with the optimal limits described above (example in Figure 27) can be used to obtain an indication of the expected performance of the material on the road. Local calibrations of the grading coefficient and shrinkage product ranges may be needed. Examples of local refinements could include but are not limited to lowering the upper level of the shrinkage product (e.g., to 250) range on roads with high truck traffic volumes or in areas with high annual average rainfall and/or high intensity storms; or reducing the lower level of the shrinkage product range (e.g., to 50 or 75) for roads with very low traffic volumes and/or slow moving vehicles. For local calibrations, practitioners can sample materials from good and poor performing roads in their jurisdiction, test these materials, analyze the results according to Step 1 above, and plot the results on the chart shown in Figure 27. The grading coefficient and shrinkage product ranges can then be adjusted to accommodate these local performance observations and future material acquisitions based on these defined ranges.

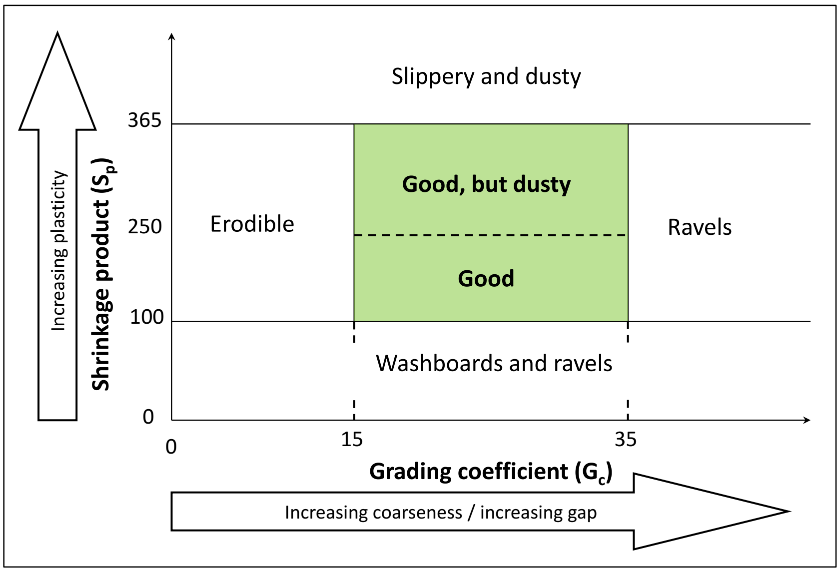

Figure 27: Material performance predictor chart (adapted from Paige-Green, 1989)

The following factors that contribute to the predicted material performance are discussed below (Jones, 2013):

- Erodible materials are typically fine grained and have some plasticity. They generally perform well when used in roads on flat terrain or in areas of very low rainfall. In other areas they will quickly erode during rainfall, leaving channels in the road that are dangerous and unpleasant to drive over and expensive to maintain.
- Materials that washboard (corrugate) and ravel are usually poorly graded or gap-graded (absence or insufficient quantities of certain aggregate sizes leading to poor aggregate interlock) and lack fines and plasticity. Consequently the particles do not bind together, leading to washboarding, raveling and, ultimately, gravel loss, and thus a poor and unsafe ride on a surface requiring regular maintenance. These materials are also prone to erosion during rainfall.
- Materials that ravel have some plasticity, but are gap-graded. The presence of clay usually limits washboarding but does not prevent raveling. Windshield damage is a major problem on these roads.
- Materials that are both slippery when wet and very dusty when dry typically have high fines (and silt and/or clay) contents. Increasing clay content also results in decreasing CBR, leading to poor passability in addition to the slipperiness.
- Well-graded materials with a small percentage of clay will perform well with a minimum of maintenance. Well-graded materials with moderate clay contents will also perform well, but may be dusty during dry conditions if the percent passing the 2.36 mm sieve is high.

5.1.3. Step 3 – Material Selection Decision

If the selected unpaved road materials falling within the "good performing area" on the chart (Figure 27) are readily available, the decision to use these materials is easy: use these materials to construct a good road and keep the road in a good condition with appropriate maintenance, and if justified, apply a suitable chemical treatment. If these materials are not readily available the practitioner needs to decide on an appropriate course of action. The following suggestions can be used as guidance in such situations (Jones, 2013):

- Weigh the consequences with the probability of occurrence:
    - Erodible materials can be used in flat areas and areas with low rainfall or low intensity rainfall events. Chemical treatments may reduce the erosion problem, but are unlikely to prevent it.
    - Materials that washboard or ravel can be used on roads with low-traffic volumes traveling at low speeds or where the road carries mostly laden heavy vehicles travelling at low speeds. They can also be used if the practitioner is prepared to regularly blade or drag the road. The costs of this frequent maintenance should be compared with the cost of importing better quality gravel from elsewhere. If the road is generally only used to access residences, the homeowners may be willing to tow a simple tire drag themselves to smooth washboarding and raveled areas. Chemical treatments will retard the rate of washboarding, but won't prevent it. They will not prevent raveling.
    - Materials that are slippery or impassable can be considered on low traffic volume roads in low rainfall areas if the road can be closed during problem events. Some

chemical treatments can be used to modify or "waterproof" the clay particles causing the slipperiness. Appropriate signs warning of potential slipperiness should be provided.
    - Good but dusty materials can be used with appropriate speed restrictions (less than 50 km/h) or with the use of a suitable dust palliative.
- Use the material "as is," but adjust maintenance programs accordingly:
    - Blade the road more frequently to remove erosion channels or washboarding and redistribute raveled material.
    - Close the road during slippery or impassable conditions, such as after heavy thunderstorms, prolonged rainfall, or during spring thaw.
- Seek alternative aggregate suppliers who can provide the requested material.
- Blend two materials to meet the required grading coefficient and shrinkage product. This usually requires the addition of small amounts of clay if commercially obtained crushed aggregate is used.
- Use a chemical treatment at higher than normal application rates to provide additional binding to the material, but remember that it is usually cheaper to use fines to fill voids (i.e., meet the grading coefficient and shrinkage product requirements) than to use a chemical. (Jones, 2013).

It has been clearly shown internationally that roads constructed with materials that are processed to meet the requirements of good materials identified in Figure 27, and when constructed according to specification, result in significant improvements in performance as well as from 50 to 60% reductions in gravel loss compared to what are considered more "conventional" strategies. Entirely new maintenance strategies have evolved around these findings in road agencies that have adopted this alternative approach (Jones, 2013).

5.2. Roadway Geometric Design Considerations

A number of elements are critical to building and maintaining a gravel road, especially unpaved roads that commonly experience heavy truck traffic.

Roadway width is determined by the type and volume of traffic on a roadway. Higher traffic volumes and speed necessitate wider roadways. However, roads that are too wide require large volumes of wearing course gravel and can lose their shape quickly. Conversely, narrow roads can lead to rutting and compromised safety. Road widths tend to vary from 4 to 9 m. Recommendations from the South African TRH20 and Unsealed Roads Manual suggest the following:

- 1 lane of 5 to 6 m wide for less than 50 VPD.
- 1 lane of 6.5 to 7.5 m wide for between 50 and 200 VPD
- 2 lanes totaling 8 to 8.5 m wide for more than 200 VPD or for roads with high truck traffic (Guimmarra 2009, Republic of South Africa Department of Transport 2009).

Gravel roads should have a **crowned driving surface**. The recommended range of crown to ensure optimal performance, effective drainage, and maintain safe driving conditions is between 4 and 6%. Insufficient crown can lead to standing water on the roadway surface causing puddles that can lead to potholes, rutting, and impassable conditions, while excessive crown can lead to unsafe driving conditions and erosion of the wearing course aggregates (Republic of South Africa Department of Transport 2009, Skorseth and Selim 2000). Ruts are also caused by vehicles travelling on base and wearing course layers that are either too thin or are constructed with inappropriate materials. Ruts influence drainage by channelizing water and creating new erosion problems and can lead to impassable conditions (Keller et al., 2011). Reducing tire pressure has also been shown to reduce rutting depth (Keller et al., 2011) on perpetually wet roads.

Proper crown on a roadway is achieved by shaping with a motor-grader. The following suggestions can aid in achieving appropriate crown on an unpaved road surface (Skorseth and Selim, 2000):

- Operating speed of the motor-grader is important and should be maintained between 5 and 8 km/h. Higher speeds can induce bouncing of the cutting blade, which will cause ridges and indentations to form in the roadway surface.
- The angle of the blade should be set between 30 and 45 degrees. Recovering material from the shoulder of the roadway is easier within this range and reduces spillage.
- The tilt, or pitch, of the cutting blade is also important (Figure 28). Proper angling can reduce accumulation of material at the shoulder of the road, which can reduce or impact drainage from the road surface. Altering the angle of the cutting blade can also make addressing different types of maintenance issues easier. Angling the cutting edge of the blade:
    - Leading into the ground is recommended for aggressive cutting.
    - Vertical is ideal for scraping or planning.
    - Forward is ideal for dragging material.

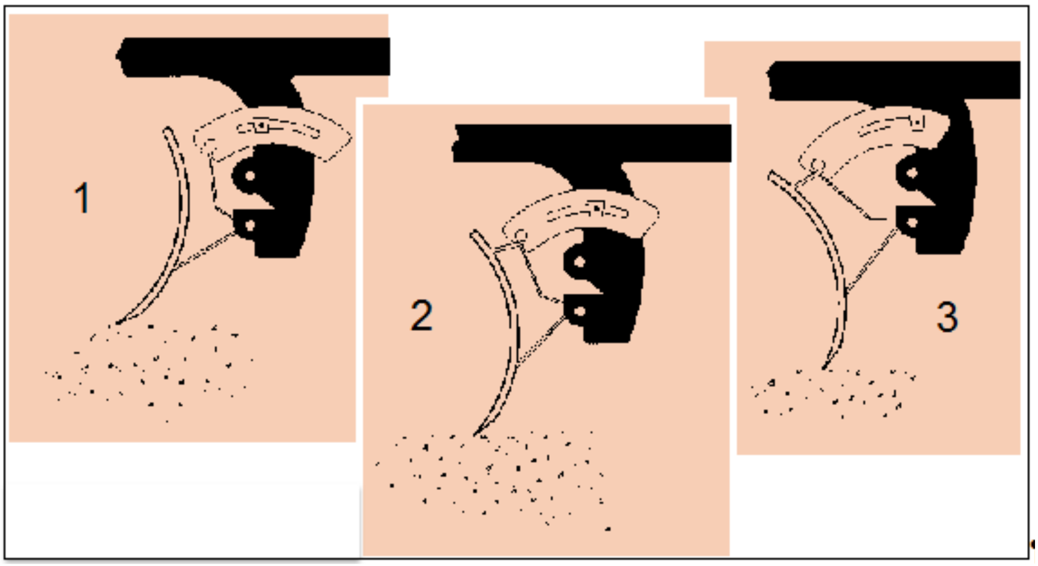

Figure 28: Examples of how the tilt, or pitch, of the cutting blade can be modified to achieve varying results (Skorseth and Selim, 2000).

Occasionally, a phenomenon known as parabolic crown can occur due to excessive wear on equipment cutting blades near the center of the blade. Parabolic crown can adversely affect drainage causing puddling and subsequent pothole formation in the center of the roadway. Care should be taken to ensure that cutting blades are maintained to cut straight, or that alternatives to reduce parabolic crown, such as long-wearing carbide blades, are considered (Skorseth and Selim 2000).

The **shoulder of the road** serves many important functions, by providing support to the edge of the road surface in addition to serving as a recovery area for vehicles to regain control. Perhaps the most important function of the shoulder is to serve as a means of carrying water away from the road surface.

The shape of a shoulder area is important to ensure proper function. The shoulder should be at the same elevation of the roadway to minimize safety hazards that may occur from a sharp change in slope between the shoulder and road surface and to maximize support for the roadway edge. Care should be taken that shoulders not become higher than the road surface as this can reduce the efficacy of drainage and lead to a host of maintenance issues. Remedying erosion at the roadway edge and seepage into the subgrade can be difficult and costly maintenance efforts, which can be prevented by proper shoulder construction. Examples of Cost-Effective and Sustainable Road Slope Stabilization can be found in NCHRP Synthesis 430 (http://onlinepubs.trb.org/onlinepubs/nchrp/nchrp_syn_430.pdf).

Improperly shaped shoulders can result from incorrect pitch on the cutting edge of the motor-grader resulting in a loss of material from the toe of the blade. Other contributing factors to high shoulders include the migration of loose material to the outer edges of the roadway from frequent and fast traffic, vehicles travelling near the edge of the roadway, and heavy truck loads that may use more of the roadway surface than smaller vehicles (Skorseth and Selim 2000).

An example cross-section of an unpaved road is shown in Figure 29.

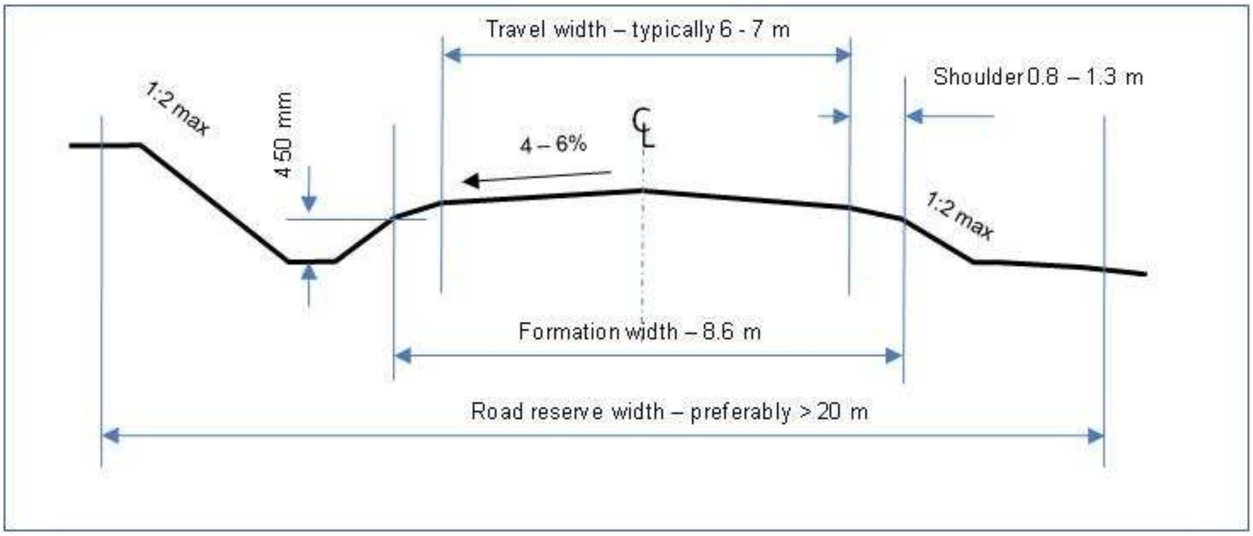

Figure 29: Cross section of a well-constructed gravel road (recreated from Republic of South Africa Department of Transport 2009).

When traffic wear causes the road to become significantly out of shape for the desired cross-section, **reshaping** should be undertaken with a motor-grader (Skorseth and Selim, 2000). The best time to reshape the road surface and road shoulders is after the rain season, when the materials have some moisture. Reshaping is accomplished by cutting material with the motor-grader and then distributing it to achieve the correct shape and percent crown, followed by roller compaction which will improve the finished surface, leaving a denser, stronger, and smother surface that will be easier to maintain.

5.3. Dust Control and Stabilization

Dust generated from unpaved roads can have significant health, environmental, and economic impacts. Dust can reduce crop yields, impact air quality leading to respiratory difficulties, and create safety concerns due to reduced visibility. Even under ideal road conditions, dust can reduce visibility to near zero. Loss of material from the road surface can also be costly and result in increased maintenance (Guimmarra 2009). Dust control and stabilization are often discussed as discreet practices, but have many aspects that overlap in that some stabilizers will also reduce dust.

Dust control reduces the loss of fine particles from the road surface, which will result in reduced wear of the aggregate on the road surface. Retaining the fines fraction of an unpaved road surface has many benefits:

- Reduced dust
- Reduced permeability at the surface of the road
- Reduced vehicle operating costs associated with rough roads
- Reduced pavement replacement and therefore reduced material cost
- Reduced economic losses from impacted agriculture and stock
- Reduced PM 2.5 emissions (particles less than 2.5 microns that tend to stay in the air causing air pollution)
- Increased visibility and safety
- Increased traveler comfort, especially in hot, dry conditions

Choosing the appropriate dust suppression or stabilization products and application technique depends on the road material properties, construction quality, traffic, and climate. Vehicle traffic volume and type is important. For traffic volumes over 250 vehicles per day (VPD) it may be more economical to seal the road with a bituminous chip seal than to regularly apply a dust suppressant or stabilizer (Lunsford and Mahoney 2001).

5.3.1. Types of Unpaved Road Chemical Treatment

Most unpaved road chemical treatments can be categorized into one of the following seven main categories:

- Water and water with surfactant
- Water absorbing
- Organic non-petroleum
- Organic petroleum
- Synthetic polymer emulsion
- Concentrated liquid stabilizer
- Clay additive (used for mechanical stabilization)

The seven categories and their sub-categories are discussed below (Jones [2013]). Additional information on each category with respect to uses, origin, attributes, limitations, application, and potential environmental impact is provided in the Appendix (Jones, 2013). Suggested specifications for each product category are provided in Jones (2013).

Water and Water with Surfactant

Water is probably the most commonly used dust suppressant. It provides a temporary agglomeration of fine particles, preventing them from being entrained by vehicles or wind. The period of agglomeration, which is affected by material properties, temperature, and relative humidity can be slightly extended with the use of selected surfactants. Repeated applications of water are required to maintain acceptable levels of dust control, which entails the necessity of application equipment dedicated to the task and, although the water itself is usually inexpensive, the cost of operating and maintaining the dedicated equipment often results in water being the least cost-effective dust control option. A number of other disadvantages arising from the regular use of water have been identified, and include slipperiness, pumping of fines to the surface (which aggravates the dust problem and causes material segregation leading to washboarding and raveling), potholes, erosion, and adhesion of mud to vehicles. The use of polluted water for dust control (e.g., on industrial and mine haul roads) can result in corrosion and runoff, and leachate can affect surface and groundwater resources over time. Since the average annual rainfall is low in many areas where dust control is practiced, the continual spraying of significant quantities of water onto unpaved roads is often regarded as an unacceptable practice, especially in circumstances where limited water resources could be used for domestic or agricultural purposes. Given these concerns, the use of water as a dust control treatment is recommended only for very short-term dust control activities where an alternative chemical treatment is not practical or cost-effective.

Water Absorbing

The most common treatments in this category are calcium chloride and magnesium chloride. Sodium chloride brines are used to a much lesser extent. These hygroscopic treatments function by absorbing small quantities of water from the atmosphere, which agglomerates the fines and holds the aggregate matrix together through suction forces.

There is a considerable published record on the use of calcium and magnesium chloride and a significant history of application. They are both most effective when used for dust control and fines preservation in either topical or mix-in applications. Although marginal increases in strength are possible over time, mostly due to improved compaction, they are water soluble and do not provide sufficient strength improvement to warrant consideration as soil stabilizers. Roads treated with these products can be maintained with conventional unpaved road techniques (i.e., motor-grader blading after light rain or water application).

Organic Non-Petroleum

This category includes, but is not limited to glycerin-based treatments, lignosulfonates, molasses- and sugar-based treatments, plant oils (e.g., soy, linseed, rapeseed, canola, or palm oils), and tall oil pitch rosins. The main constituents in organic non-petroleum treatments are mostly derived from plants and act as a “glue” that agglomerates the fines and coarser particles together. Blends of one or more of these treatments or blends of one of these treatments with calcium or magnesium chloride, base/mineral oils, synthetic fluids, or synthetic polymers are increasingly being used. They are often by-products from plant-based industries. Their composition is variable and depends on the plant matter and chemicals used during processing. Most are water-soluble. They are most effective when used for dust control or fines preservation, either as topical or mix-in treatments. They rarely provide sufficient sustained strength improvement for consideration as soil stabilizers unless blended with another binder. Treated roads can generally be maintained with conventional unpaved road techniques (i.e., motor-grader blading after light rain or water application), although some treatments may need to be reapplied after maintenance.

Glycerin Based

Most glycerin is derived from renewable resources (plant or animal based), and to a lesser extent from biodiesel production processes or petroleum feedstock. Various grades of glycerin are available, with technical grade (between 95 and 97% pure) generally being blended with other organic non-petroleum products (e.g., lignosulfonate and tall oil pitch rosin) for unpaved road chemical treatments. In addition to the humectant (moisture retaining) properties of the glycerin, the blends act as glue that agglomerates the fines and coarser particles together, but usually with enhanced binding and leaching resistance properties compared to that of single products.

Lignosulfonate

Lignosulfonates are produced as by-products during pulp and paper production. Attributes depend on the chemistry (calcium-, ammonium-, or sodium-based) used in the separation of the lignin and the cellulose. Effectiveness varies based on the plant species from which the lignosulfonate was obtained, the sugar content, and the percentage lignosulfonate content in the solution. Lignosulfonates in powder form are more consistent, but more expensive to produce and consequently are more commonly used in applications of higher value than unpaved road dust control (e.g., concrete additives, drilling fluids, and binders in animal feed). Lignosulfonates generally impart a dark color to the road surface.

Molasses/Sugar

Molasses and sugar-based treatments are produced as by-products from sugar refining. Attributes and effectiveness depend on the process used to process the plants and the type and quantity of complex sugars remaining after refining. Improvements in sugar refining processes have generally resulted in lower dust suppression effectiveness and frequent rejuvenations may be required. Use is typically restricted to roads in relatively close proximity to sugar refineries.

Plant Oil

Plant oils are by-products from food processing of various crops. Those most commonly used in unpaved road treatments include soybean, linseed, rapeseed, canola, corn, and palm oils. Performance is dependent on the level of processing. As with other plant-based treatments, competing industries with higher value uses may limit availability of these oils for unpaved road treatments.

Tall Oil Pitch Rosin

Tall oil, or "liquid rosin", is another by-product from processing tree resin during wood pulp manufacture. As with lignosulfonate, attributes depend on the chemistry used in the separation of the cellulose, and on the tree species used. Tall oils have a wide range of high value applications including adhesives and emulsifiers, and are consequently not widely available for unpaved road treatments. They have better water resistance compared to other organic non-petroleum treatments.

Organic Petroleum

These treatments are derived from petroleum refining and include diluted asphalt emulsions, base and mineral oils, petroleum resins, and synthetic fluids. Asphalt emulsions, petroleum resins, and synthetic fluids with binders, when mixed into the soil, will have a cementing action providing both fines preservation and stabilization. Base oils and synthetic fluids without binders are generally used for dust control/fines preservation and provide limited strength improvement.

Asphalt Emulsion

The use of asphalt emulsions for dust control and stabilization on unpaved roads is typically limited to slow-set emulsions (SS-1). The use of other types of emulsions (e.g., medium- and rapid-cure) is generally limited in many areas because of air quality concerns related to the volatiles that are released while the emulsion is breaking. The use of asphalt emulsions for spray-on fines preservation/dust control is generally limited by the length of the drying/curing period required before treated surfaces can be trafficked. When mixed into the soil, they provide both fines preservation/dust suppression and stabilization and are effective on sandy soils. Asphalt emulsions typically form a hard crust that cannot be maintained with a motor-grader.

Base/Mineral Oil

These treatments are produced from crude oil through physical separation processes. They do not dissolve in water and cannot be diluted prior to application. Although non-soluble in water, they can be displaced from soil particles by rainfall or watering. Base oils are effective for fines preservation/dust control, but will have limited effect on strength unless mixed with a binder (e.g., organic non-petroleum, other organic petroleum, or synthetic polymer emulsion treatment). They do not form a crust and can be maintained with conventional unpaved road maintenance techniques without any significant loss in effectiveness. A light rejuvenation may, however, be required to maintain full effectiveness.

Petroleum Resin

These treatments are a combination of petroleum resin (derived from refinery vacuum tower bottoms processing highly paraffinic crude oils), water, emulsifiers, surfactants, and vacuum residuum. Petroleum resins are insoluble in water and will not leach from the road. They generally impart a dark color to the road surface. Petroleum resins typically form a weak crust on the road surface, which can be maintained with a motor-grader after light watering without any significant loss in effectiveness. A periodic light rejuvenation may, however, be required to maintain full effectiveness.

Synthetic Fluid and Synthetic Fluid with Binder

Synthetic fluids have similar general properties and performance to base oils, but are produced from a reaction of specific purified chemical feedstock as opposed to simple physical separation. Synthetic fluids are also distinguished from base oils in terms of a United States Environmental Protection Agency (EPA) definition (U.S. EPA 40 CFR part 435). The more complex synthesis production process results in a more refined product, which although usually more expensive to purchase, has less environmental impact and consequently less restrictions on where it can be used. Like base oils, they do not dissolve in water and cannot be diluted prior to application, but can be displaced from soil particles by rainfall or watering. Synthetic fluids are effective for fines preservation/dust control, but will have limited effect on strength. They can be blended with a binder (e.g., organic non-petroleum, other organic petroleum, or synthetic polymer emulsion treatment) for use as a combination dust suppressant/stabilizer. Synthetic fluids do not form a crust and can be maintained with conventional unpaved road maintenance techniques without loss of effectiveness. Synthetic fluids with binders can be maintained with a motor-grader after light watering without any significant loss in effectiveness. Light rejuvenation after maintenance may, however, be required to sustain full effectiveness.

Synthetic Polymer Emulsion

These treatments include, but are not limited to acrylates (homopolymers and co-polymers), acetates (homopolymers and co-polymers), and styrene butadiene co-polymer emulsions, either neat or in combination. They are usually manufactured specifically for unpaved road treatments; however, some products are derived from waste streams from paint, adhesive, and other industrial applications. Synthetic polymers are thermoplastic in nature, providing a flexible bond with the aggregate particles. They can be diluted in water when applied, but once dry should not re-emulsify or leach from the road. They are often not effective as spray-on applications due to their forming a “skin” on the surface of the road that typically abrades relatively quickly under traffic. However, some manufacturers have introduced specific formulations that when applied as a spray-on application, will penetrate the soil to a sufficient depth to adequately bind the particles without forming a skin on the surface. As mix-in treatments, they can be used for both fines preservation/dust control and stabilization. Treated roads can generally not be maintained with conventional unpaved road techniques and typically require reapplication after motor-grader blading.

Concentrated Liquid Stabilizers

Concentrated liquid stabilizers are a group of treatments that are all proprietary in nature, with little published information on their exact composition and stabilization mechanisms. Consequently, they are difficult to group and classify accurately. They stabilize the soil in a complex electro-chemical and/or enzymatic cementing bond that reduces the soil’s affinity for water. Studies indicate that acidity is one appropriate method of grouping these treatments. Although binding of fine particles does occur in a successful reaction, the level of fines preservation/dust control is often insufficient for the treatments to be considered as dust palliatives. In these instances, a separate dust suppression treatment may have to be used on top of the stabilized surface to reduce fines loss/dust to an acceptable level. Treated roads can generally be maintained with conventional unpaved road techniques (i.e., motor-grader blading after light rain or water application).

High Acidity Concentrated Liquid Stabilizers

These treatments (also termed electrochemical additives, sulfonated oils, sulfonated petroleum products [SPPs], or ionic stabilizers) rely on ionic exchange reactions to perform their expected functions satisfactorily. Their "active ingredients" are mostly hydrocarbon mineral oils modified with sulfuric acid to form a sulfonic acid. Sulfonated oils are all "surface active agents" (surfactants) and have the ability to fix, displace, or replace exchange cations in clays and to render the soil materials (particularly clay minerals but not necessarily only clays) hydrophobic by displacing adsorbed water and water of hydration. The reaction should also prevent readsorption of this water. They are highly susceptible to ion exchange reactions in which appropriate inorganic ions present on mineral surfaces (particularly clays) and in clay interlayers are replaced by, or attached to, the organic molecules. This reduces the mobility of the ions and functionally reduces the plasticity of the material. Once an ion exchange reaction has occurred and the sulfonic acid is attached to a mineral particle, the so-called hydrophobic tails of the sulfonated oils are directed away from the particle and form an oily protective layer around it. In theory, this has the effect of reducing the thickness of the electrical double layer and of preventing water from gaining access to the clay mineral particle. With this reduced double layer thickness, it now becomes theoretically possible to achieve a greater degree of compaction in the material, with resultant higher shear strengths and reduced water absorption of the material in the long term.

Low Acidity/Neutral Concentrated Liquid Stabilizers

These treatments are mostly enzymatic emulsions containing protein molecules that lower surface tension in water and catalyze very specific chemical reactions with soil molecules to form a cementing bond that stabilizes the soil structure and reduces the soil's affinity for water. Theoretically, they will work on a wider range of soils than high acidity treatments (which require relatively high clay contents, and sometimes specific clay minerals, for a satisfactory reaction) but still require a presence of clay and relatively high fines content (typically more than 20% passing the 0.075 mm sieve). Although the actual stabilization mechanism is less well understood than that of high acidity stabilizers, the end result and performance is similar. Better compaction associated with the surfactant properties of the additive can increase density and soil strength, and reduce pore water leading to better resistance to moisture intrusion.

Clay Additives

Clay additives are used to mechanically stabilize unpaved road materials that have low fines contents. Bentonite is the most commonly used clay additive, but other clays such as montmorillonite have also been used successfully. Application rates are based on grading analyses and plasticity index (or preferably shrinkage product). Thorough mixing of the clay into the existing material is required for optimal performance and to prevent localized soft spots. Although the addition of clay does lead to agglomeration of fine particles, the level of fines preservation/dust control is often insufficient for clay additives to be considered as dust palliatives. In these instances, a separate dust suppression treatment may have to be used on top of the mechanically stabilized surface to reduce fines loss/dust to an acceptable level. Treated roads can be maintained with conventional unpaved road techniques (i.e., motor-grader blading after light rain or water application).

5.3.2. Effect of Chemical Treatments on Unpaved Road Performance

The unpaved road chemical treatments discussed above will agglomerate fine materials and/or provide some level of "waterproofing", which in turn can improve all-weather passability. Although the best possible materials should be used for wearing courses on unpaved roads, as described above (and illustrated in Figure 27), the use of an appropriate chemical treatment can lead to acceptable performance over a larger range of shrinkage product and grading coefficient due to this agglomeration and/or waterproofing. Improvement in expected performance due to the different chemical treatment categories are shown in Figure 30 and can be used to better understand the selection of appropriate treatments for a specific material. Guidance on how various chemical treatment categories perform in terms of the material grading coefficient and shrinkage product is as follows (Jones, [1999]):

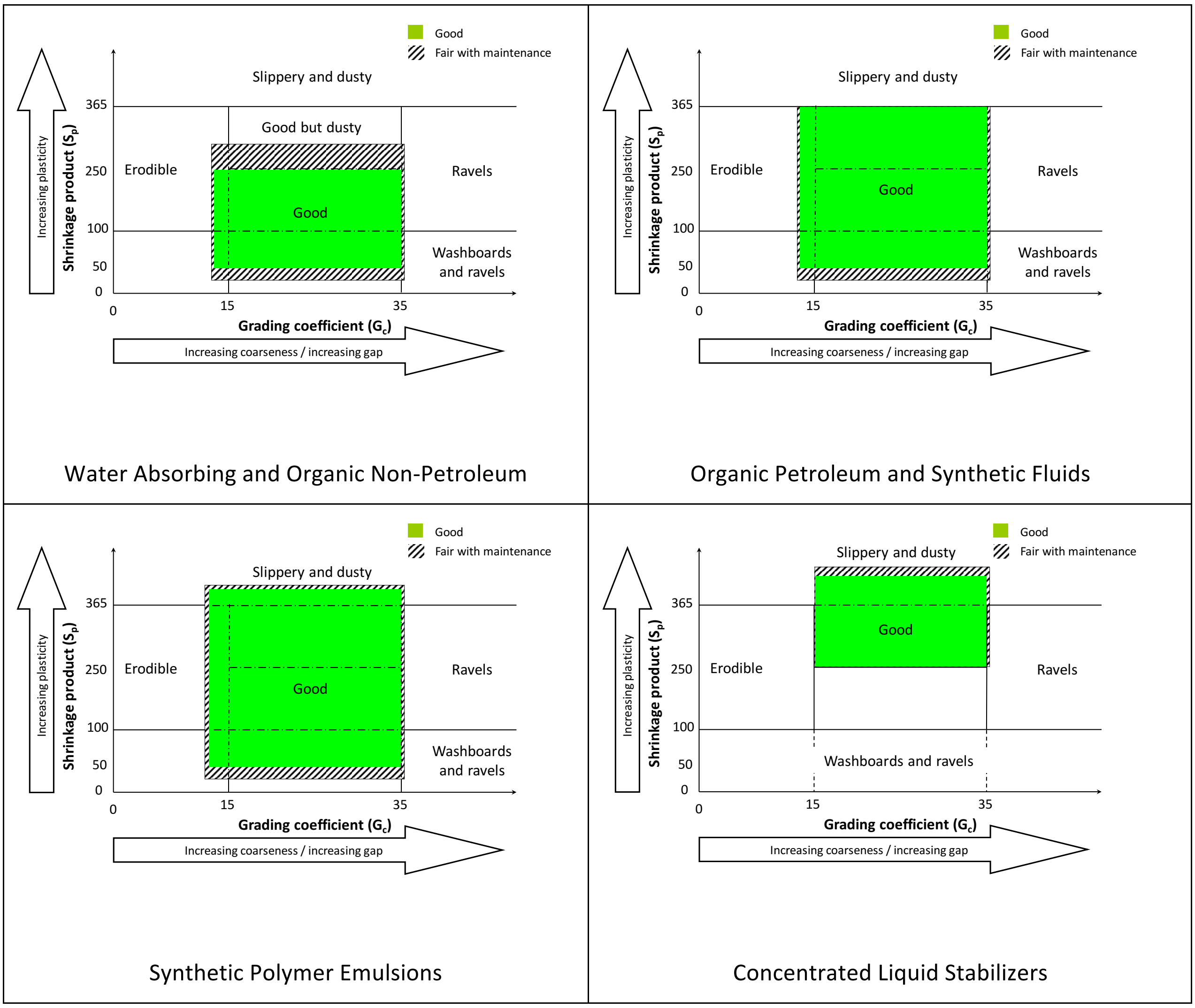

Figure 30: Expected Performance of Unpaved Roads after Chemical Treatment.

Erodible Materials

The problems with erodible materials are usually grading and/or drainage related, both of which are difficult to overcome with chemical treatments. Non-water-soluble polymer emulsions or bituminous-based treatments can be tried on gentle to moderate slopes in combination with drainage improvements. Water-soluble treatments (for example, chlorides and plant-based polymers such as lignosulfonate) will reduce dust, but will not prevent erosion. Neither will concentrated liquid stabilizers, as the clay content is usually insufficient for a reaction that will bind the particles satisfactorily to prevent the shear action of flowing water. Increased compaction (often enhanced by some of the chemical treatments that also perform as compaction aids) in combination with optimal drainage design and control will also assist in reducing erosion.

Materials that Washboard and Ravel

These materials lack fines and plasticity. Depending on the traffic, chemical treatments lose effectiveness if the shrinkage product is less than 50 because uneconomically high application rates are required to fill the voids between the particles. Wind-shear and tire-shear forces usually also exceed the binding ability of the treatments used under these circumstances, leading to continued problems. If the shrinkage product is above 50, most chemical treatments except concentrated liquid stabilizers (these typically require much higher plasticity to react effectively) can be used to improve the materials by enhancing binding, leading to significant reductions in dust and washboarding. Incorporating a clay additive (e.g., bentonite) or other source of fines (often readily available from adjacent land owners or waste piles at quarries), can be considered to raise the shrinkage product to 50 before applying an appropriate chemical treatment.

Materials that Ravel

Chemical treatments are generally ineffective on these materials because of the coarse- or gap-grading. They will control dust initially, but will not prevent the raveling. Some success may be achieved at very high application rates (i.e., using the chemical to fill the voids before a satisfactory bond is obtained). Alternatively, the addition of the "gap" material can be considered to adjust the grading coefficient before treatment. If the grading is not adjusted, dust levels will increase as the coarse material gets displaced to the side of the road under traffic.

Slippery or Impassable Materials

Chemical treatments used on these materials need to either chemically alter the clay minerals to reduce the plasticity or "waterproof" the clay particles to prevent them from expanding/shearing when wet. Synthetic polymer emulsions, synthetic fluids with binders, and concentrated liquid stabilizers can be considered. Atterberg Limits and soaked CBR tests should be carried out to check that a suitable reduction in plasticity and/or sufficient increase in soaked shear strength (e.g., CBR) is achieved with the selected treatment before it is applied on the road. Depending on the material grading, it may also be necessary to increase the percentage of coarser aggregate to improve tire/road friction. Chlorides and other water-soluble treatments (e.g., most organic non-petroleum treatments) should not be considered for treating slippery or impassable materials.

Good and Good but Dusty Materials

Most chemical treatments can be effectively used on roads with these materials to minimize dust and limit fines loss, reduce the rate of gravel loss, and increase the intervals between motor-grader maintenance. All chemical treatment categories except concentrated liquid stabilizers (clay contents are typically too low for these to work effectively) can be considered.

5.3.3. Choosing a a Dust Suppressant

A new approach to the selection of an appropriate chemical treatment for a given set of conditions was recently developed and is described in detail in Jones (2013). The approach is based on the practitioner understanding the roads that require treatment in terms of traffic, climate, geometry, and materials (as discussed above); understanding the different chemical treatment categories (as discussed above); and understanding the objective for applying a chemical treatment (e.g., short- or long-term dust control, or stabilization). Based on the information collected, the most appropriate chemical treatment categories for a given situation can be selected from a series of charts and ranked using a simple arithmetical formula. The ability to rank the different treatments available differentiates this procedure from other procedures documented in the literature. Basic guidance on environmental considerations, effect of soil chemistry, and maintainability with a motor-grader is also covered in the selection procedure.

An accurate indication of the fines content (passing the 0.075 mm sieve) and the plasticity index (or linear shrinkage) are required as material inputs for the selection procedure and for obtaining an indication of likely performance after treatment (as shown in Figure 30). As discussed above, these tests are inexpensive, and practitioners are encouraged to run tests on the actual materials that will be treated (sampled from the road or quarry stockpile) rather than guess the values.

5.3.4. Considerations for Applying Chemical Treatments

The application of chemical treatments are discussed in detail in Jones (2013). Key considerations are discussed below.

Once a suitable product is selected, the next step is to determine the appropriate application rate and frequency. Manufacturer's literature, past experience, and field or laboratory tests can also be used to help determine the appropriate application rate. Generally, higher application rates or increased frequency is required when the following conditions are present:

- High traffic volumes with high speeds and a larger percentage of truck traffic
- Low humidity conditions, especially when using chlorides
- Low fines content in road surface, typically when there is less than 10% passing the the 0.075 mm sieve
- Poorly bladed surface and/or loose wearing surface.

The performance of any chemical treatment is related to the application method, rate, frequency, and product concentration, etc. A stable, tight surface that readily sheds surface water is another. If properly applied and constructed, a longer life and higher level of service can be expected from the dust abatement efforts. Since chemical treatment and road maintenance efforts are usually combined, include the following practices in the maintenance and rehabilitation of road surfaces prior to applying a dust palliative:

- Repair unstable surfacing and/or subgrade areas
- Adequately drain (crown and crossfall) the road surface
- Remove large aggregates in the surface material
- Grade sufficient depth of roadway to remove ruts, potholes, and erosion gullies
- Compact the roadway (depending on treatment and sequence of operations).

Maximum benefits can also be achieved by adequate penetration of liquid chemical treatments. This penetration should be on the order of 10 to 20 mm. Proper penetration mitigates loss of the treatment resulting from surface wear. Adequate penetration also resists leaching, imparts cohesion, and resists aging. Application tips that apply to all liquid chemical treatment products include:

- The road must be appropriately prepared prior to application of the product. Emphasize that chemical treatments do not make a bad road good; they only keep a good road good. Quality surfacing materials and a well-shaped road that easily sheds water are critical to the performance of all unpaved roads, and those receiving chemical treatment are no exception.

- Adhere to the correct application procedure for the selected additive is imperative. Different additives require different application methods (typically spray-on or mix-in and the additive supplier must provide detailed instructions and guidance on how to do it correctly. Note that some spray-on applications require a series of light applications to achieve the desired penetration as opposed to a "single shot," which could run off into side drains, where it serves no purpose and could have negative environmental consequences. Adhere to manufacturers' recommendations on minimum application rate, compaction and curing time prior to allowing traffic (example construction specifications are provided in Jones [2013]). All products intended for stabilization must be mixed into the road surface. Dust suppressants will also last longer if mixed into the surface material, but most can be sprayed directly onto the surface if mixing equipment is not available, although more regular rejuvenation treatments will be required.
- Where possible, apply chemical treatments after rain so materials are more moist (aids mixing) and more workable. If applied just before rain, the treatment may leach out.
- Dampen the surface with a light spray of water prior to application of spray-on treatments to assist with penetration. A light scarification of the surface will also assist with penetration and prevent runoff.
- If a hard crust is present, break up and loosen the surface.
- Use a pressure distributor to uniformly distribute the chemical treatment (i.e., do not use gravity feed spray equipment). Ensure that all application equipment is correctly calibrated
- Compact the road surface after treatment to seal the surface.
- Unscheduled maintenance can do more harm than good. Most chemical treatments form some type of crust and if this is unnecessarily broken up, it will lead to increased levels of dust, rapid deterioration of ride quality, moisture loss, loose aggregate (which can cause windshield damage), and ultimately washboarding—all of which mean additional gravel will be needed sooner, greatly increasing the cost of maintaining the road.
- The periodic maintenance typically associated with chemical treatments (that is, usually once or twice a year on roads with typical unpaved road traffic) should not simply cover surface distresses with material from the sides of the road. Instead, the surface crust should be softened with a water spray and then reshaped to restore the crown and remove any deformations (or this can be done after light rain). Applying a water spray also allows remixing of the surface material and prevents a "biscuit" layer from forming. Biscuit layers rapidly break up under traffic, leading to a rough ride. Other chemical treatments form more permanent non-water-soluble surfaces, which require the use of scarifiers or rotomilling to break up the surface. Again, different types of treatment require different maintenance techniques and the additive supplier must provide clear guidance and training

5.4. Managing Unpaved Roads as a Program

Managing unpaved roads in a programmatic way can improve future management by learning from successes and failures. Factors to be considered when establishing an unpaved road program are outlined below from work by Jones et al. (2013).

Documentation of the features of the unpaved roads in the network are critical, including a survey of the road and adjacent land, and possibly working with the road users and those who live next to it to understand public perceptions of problems with the road. Information that should be collected includes:

- Road alignment and geometry, including drainage and the presence of shoulders, and highlighting any areas that typically require additional maintenance and/ or repairs, or that are considered accident "black spots." The steepness of the grade may limit the choice of chemical treatment.
- Adjacent land use, such as residential, crops, forest, and wetland.
- Road condition, (poor, average or good) with a reason for the rating (no or poor aggregate, inadequate drainage, dust, surface distresses of washboarding, potholes, ruts, erosion, and weak subgrade). Problems should be divided into those that can be corrected using routine maintenance and those that will require reconstruction and/or regravelling.
- The thicknesses of the wearing and base courses and their material properties (using simple laboratory tests that determine the particle size distribution [grading] and plasticity [Atterberg Limits].
- The ability of the road to shed water (Is there sufficient crown?). A crown of between 4 and 6% is adequate for water to flow off the road.
- The average daily traffic volume, primary users (for example, commuters or haul vehicles), types of vehicles (percentage of trucks and cars), seasonality of traffic (are there peak periods during harvesting), and whether there is loaded truck traffic in one direction and unloaded in the other (fast moving empty trucks tend to cause more rapid deterioration on unpaved roads than slower moving loaded trucks).
- Average speed of the vehicles and what governs this speed (for example, road condition, dust, enforcement, etc.). The road manager will need to predict whether speeds will increase after dust control and whether this will lead to unsafe driving conditions.
- Known problem areas that require constant maintenance/repair or that constantly generate public complaints and the reason(s) for the problem.
- The current regravelling and motor-grader maintenance program and frequencies.
- The current funding levels and whether additional funding can be made available if chemical treatments can be justified, and whether a multi-year program will be considered to optimize spending in the longer term.
- An acceptable level of dustiness. Complete dust control is generally only achieved by upgrading a road to a paved standard, the costs of which are often prohibitive and unjustifiable for low traffic volumes. Road users and adjacent property owners will often gladly accept a percentage of dust reduction. Ask these individuals to rate what an acceptable level of dust control is.
- The long-term plan for each road (will it continue to experience current average daily traffic [ADT] and usage types or is ADT increasing? Will it be closed or paved in the next few years? Will improving it with a chemical treatment attract more traffic?).
- Climatic conditions, including rainfall distribution and intensity of storms, annual humidity ranges, freeze/thaw conditions, and maximum temperatures.

5.5. Resources

The following list provides resources referenced in the document or additional information on this or related topics. Unfortunately these documents are mostly only available in English.

- Unpaved Road Dust Control and Stabilization Treatment Selection Guide www.ucprc.ucdavis.edu
- Gravel Roads Maintenance and Design Manual http://water.epa.gov/polwaste/nps/upload/2003_07_24_NPS_gravelroads_gravelroads.pdf
- Draft TRH 20 Unsealed Roads: Design, Construction and Maintenance
- Dust Control Field Handbook http://acwc.sdp.sirsi.net/client/search/asset/1003308
- Unpaved Road Dust Management A Successful Practitioner's Handbook http://flh.fhwa.dot.gov/innovation/publications/Materials/cflhd/Unpaved%20Road%20Dust%20Management%20A%20Successful%20Practitioners%20Handbook.pdf
- Maintenance Guide for Unpaved Roads: A Selection Method for Dust Suppressants and Stabilizers http://roaddustinstitute.info/archive/Resources/MaintenanceGuide.pdf
- Dust Palliative Selection and Application Guide http://www.ecy.wa.gov/programs/air/pdfs/Dust_Palliative.pdf
- Stabilization Selection Guide for Aggregate- and Native-Surfaced Low Volume Roads http://www.fs.fed.us/eng/pubs/pdf/08771805.pdf

5.6. Conclusions/Recommendations

This chapter summarizes best practices based on experiences internationally. We recommend starting with these best practices and testing the soils types commonly used for the roads in the Gobi Desert using tools provided in this chapter (sieve test and plasticity test). Based on the findings of these tests, a method to improve the road surface and minimize dust can be selected from information provided in the chapter, the Appendix, and supplemental resources. This chapter can also be used as a starting point for a Mongolian national guidebook on managing unpaved roads and expanded upon and adapted to local lessons learned as unpaved roads in Mongolia are monitored.

6. SUMMARY

The increased transportation activity related to mining growth in the Gobi Desert has the potential to fragment habitat for khulan, goitered gazelle and other species. If future mining growth continues, the related freight traffic could fragment the habitat to the point that the species of concern could face extinction. The following are the major transportation impacts to wildlife:

- Habitat fragmentation caused by
  - increased vehicle traffic,
  - some of this traffic being off-road parallel to paved road, creating a wider impact zone,
  - fencing adjacent to linear transportation infrastructure, and
  - tall cut and fill slopes along the Mongolian Railroad;
- Potential for increased wildlife mortality if traffic increases;
- Habitat degradation adjacent to roads due to sight of traffic and dust (for unpaved roads); and
- Increased human access resulting in an increase in poaching.

One of the geographic locations of most concern is the area where freight transport occurs to bring mining products to the Gashuun Sukhait border crossing with China. There are two roads and a partially constructed railroad. There is some good news in this area:

- Unlike the Trans-Mongolian Railroad, the Mongolian Railroad Company is building rail lines in the South Gobi without fences. The partially constructed rail line adjacent to the UK-GS Road has no fences.
- The Mongolian Railroad also includes several partially constructed wildlife underpasses.
- The slow down for coal demand in China has led to a reduction in freight traffic.
- Off-road travel adjacent to the UK-GS Road appears to be nearly eliminated.
- A permanent traffic count station has been installed on the OT-GS Road primarily to provide data for understanding traffic impacts to wildlife. Efforts also continue to collect and study wildlife movement data.

Despite this good news, efforts need to continue to protect wildlife from transportation impacts. If off-road traffic becomes an issue, efforts should be made to curtail it. Other transportation infrastructure in the South Gobi should also have limited or no fencing. The following types of data collection and research are very important:

- Traffic flow data,
- Wildlife mortality data,
- Wildlife movement data and research to answer these questions:
  - How much traffic on a roadway or railroad creates a significant barrier for various species?
  - What is the width of habitat degradation adjacent to the road for various species?
  - Do cut and fill slopes on railroads create a barrier to wildlife?
  - Where are priority wildlife corridor movements for various species?
- Mitigation monitoring.

Wildlife crossing structures are the most promising approach to mitigating against habitat fragmentation. Constructing even a limited number of crossing structures before traffic increases to become a total barrier is crucially important, so as to better understand the usefulness of particular designs to the target species. Considering the three parallel linear infrastructures (OT-GS Road, UK-GS-Road and Railroad), structures should be placed at a similar latitude for better connectivity across all roads/railroads.

Additional mitigations that could be considered include:

- Managing freight demand
- Driver awareness and public education campaign
- Time of day restrictions
- Truck platooning
- Managing road dust on unpaved roads.

7. REFERENCES

Agency of Standardization and Metrology. Mongolian State Standard: General Demands on Ungulates Crossing Across Highway and Railway. [English Translation] Ulaanbaatar City. 2014.

Bullpin consultancy Ltd. 2008. Southern Mongolian Infrastructure: Land Transport Infrastructure to Support Mining Development. World Bank Report.

Clevenger, A.P. & M.P. Huijser. 2011. Wildlife crossing structure handbook design and evaluation in North America. Publication No. FHWA-CFL/TD-11-003. Department of Transportation, Federal Highway Administration, Washington D.C., USA. Available from the internet: http://www.westerntransportationinstitute.org/documents/reports/425259_Final_Report.pdf

CMS / UNEP. 2008. Convention on the Conservation of Migratory Species of Wild Animals. Proposal: Inclusion of all subspecies of black-tailed gazelle Gazella subgutturosa in Appendix II of the Convention on the Conservation of Migratory Species of Wild Animals. Proposal II / 13. Secretariat provided by the United Nations Environment Programme. Proposals for amendment of appendixes I and II for consideration by the ninth meeting of the conference of the parties, 1-5 December 2008, Rome, Italy. http://www.cms.int/bodies/COP/cop9/Proposals/Eng/Appendix_I_&_II_Proposals_E.pdf

Delaware Water Gap National Recreation Area. 2003. Cover me! “"Nights of Migrating Dangerously”" end as the park closes River Road to protect amphibians. U.S. Dept. of the Interior National Park Service. Spanning the Gap 25 (1): Spring 2003.

Dezort, N. and McGowen, P. Dezort, N. and McGowen, P. Developing a Crash Prediction Model for Deer-Vehicle Collisions. Project Report. Western Transportation Institute Undergraduate Research Exeperience. May 2010.

Dodd, N.L., J.W. Gagnon, S. Sprague, S. Boe & R.E. Schweinsburg. 2011. Assessment of pronghorn movements and strategies to promote highway permeability. U.S. Highway 89. Report No. FHWA-AZ-10-619. Arizona Game and Fish Department. Research Branch, Phoenix, Arizona, USA. http://www.azdot.gov/TPD/ATRC/publications/project_reports/PDF/AZ619.pdf

ESIA. 2013. Environmental Social Impact Assessment. SECTION C: IMPACT ASSESSMENT CHAPTER C6: BIODIVERSITY AND ECOSYSTEM SERVICES. http://ot.mn/sites/default/files/documents/ESIA_OT_C6_Biodiversity_EN.pdf

Gavin, S. & P. Komers. 2006. Do pronghorn (Antilocapra americana) perceive roads as a predation risk? Canadian Journal of Zoology. 84: 1775-1780.

Guimmarra, G., Editor. Unsealed Roads Manual: Guidelines to Good Practice, Third Edition. Manual, Australian Roads Research Board, Vermont South, Victoria, Australia: ARRB Group, 2009.

Harris, R.B. & Reading, R. 2008. Ovis ammon. The IUCN Red List of Threatened Species. 2008: e.T15733A5074694.

http://dx.doi.org/10.2305/IUCN.UK.2008.RLTS.T15733A5074694.en

Huijser, M.P., P. McGowen, A. P. Clevenger & R. Ament. 2008. Best practices manual, wildlife-vehicle collision reduction study, Report to U.S. Congress. Federal Highway Administration, McLean, VA, USA. Available from the internet: http://www.fhwa.dot.gov/environment/hconnect/wvc/index.htm

Huijser, M., Clevenger, A. McGowen, P., Ament, R.and Begley, J. 2013. Oyu Tolgoi Roads and Wildlife Mitigation Report.. Oyu Tolgoi LLC. Ulaanbaatar, Mongolia.

Ito T.Y., B. Lhagvasuren, A. Tsunekawa, M. Shinoda & S. Takatsuki. 2013. Fragmentation of the habitat of wild ungulates by anthropogenic barriers in Mongolia. PLoS ONE 8(2): e56995. doi:10.1371/journal.pone.0056995.

Ito TY, Tsuge M, Lhagvasuren B, Buuveibaatar B, Chimeddorj B, et al. (2013b) Effects of interannual variations in environmental conditions on seasonal range selection by Mongolian gazelles. J Arid Environ 91: 61–68.

IUCN. 2013. The IUCN red list of threatened species™. http://www.iucnredlist.org/

Iuell, B., G. J. Bekker, R. Cuperus, J. Dufek, G. Fry, C. Hicks, V. Hlavác, V. Keller, C. Rosell, T. Sangwine, N. Tørsløv, and B. le Maire Wandall,. 2003. COST 341. Habitat Fragmentation due to Transportation Infrastructure. Wildlife and traffic: a European handbook for identifying conflicts and designing solutions. KNNV Publishers, Utrecht, The Netherlands.

Jackson, S. 2015. Dusty Roads and Disconnections: Perceptions of Dust from Unpaved Mining Roads in Mongolia's South Gobi Province. Geoforum Journal. 66, 94-105.

Johnston, L. 2011. Mongolia - Oyu Tolgoi Copper/Gold/Silver Mine Project Trip Report for May-June 2011. USAID, Washington DC USA.

Jones, D. 1999. Dust and Dust Control on Unsealed Roads. PhD Thesis, University of the Witwatersrand, Johannesburg, South Africa.

Jones, D., et al. Unpaved Road Dust Management, A Successful Practitioner's Handbook. Technical Report, Lakewood, Colorado: Federal Highway Administration, 2013.

Jones, D. 2013. Unpaved Road Dust Control and Stabilization Treatment Selection Guide. Davis, CA: University of California Pavement Research Center (UCPRC-GL-2013-01).

Kaczensky, P., Lkhagvasuren, B., Pereladova, O., Hemami, M. & Bouskila, A. 2015. Equus hemionus. The IUCN Red List of Threatened Species 2015: e.T7951A45171204. http://dx.doi.org/10.2305/IUCN.UK.2015-4.RLTS.T7951A45171204.en

Kaczensky, P.,, D. Sheehy, C. Walzer, D. Johnson, D. Lkhagvauren & C. Sheehy. 2006. Room to roam? The threat to khulan (Wild Ass) from human intrusion. Mongolia Discussion Papers, East Asia and Pacific Environmental and Social Development Department. Washington DC,: World Bank, USA.

Kaczensky, P., R. Kuehn, B. Lhagvasuren, S. Pietsch, W. Yang & C. Walzer. 2011. Connectivity of the Asiatic wild ass population in the Mongolian Gobi. Biological Conservation 144: 920-929.

Keller, G., and Sherar, J.. Low-Volume Roads Engineering, Best Management Practices Field Guide. Washington D.C., District of Columbia: US Agency for Internation Development, 2003.

Keller, G., Wilson-Musser, S., Boland, P., and Barandino, V. Stabilization and Rehabilitation Measures for Low-Volume Forest Roads. U.S. Forest Service. 2011.

Keshamat, S., Tsendbazar, N., Zuidgeest, M., Shiirev-Adiya, S. VanDerVeen, A. and VanMaarseveen, M. 2013. Understanding Transportation-Caused Rangeland Damage in Mongolia. Journal of Enviornmental Management. 114: 433-444.

Lian, X., X. Xiao & T. Xu. 2012. Avoidance distances of four ungulates from roads in Kekexili and related protection suggestions. Shengtaixue Zazhi 31(1): 81-86.

Lkhagvasuren, B., Chimeddorj, B. and Sanjmyatav, D. Barriers to Migration: Case Study in Mongolia, Analysing the Effects of Infrastructure on Migratory Terrestrial Mammals in Mongolia. Prepared for Convention on the Conservation of Migratory Species and World Wildlife Fund. October 2011.

Lkhagvasuren, B. 2012. National Report on the Convention on Migratory Species of Wild Animals. Ministry of Nature, Environment, and Tourism, Ulaanbaatar, Mongolia.

Lunsford, G., and Mahoney, J.. Dust Control on Low Volume Roads: A Review of Techniques and Chemicals Used. Technical Study Report, Federal Highway Administration, U.S. Department of Transportation, Seattle: Federal Highway Administration, 2001.

Mallon, D.P. 2008a. Gazella subgutturosa. The IUCN Red List of Threatened Species 2008: e.T8976A12945246. http://dx.doi.org/10.2305/IUCN.UK.2008.RLTS.T8976A12945246.en

Mallon, D.P. 2008b. Procapra gutturosa. The IUCN Red List of Threatened Species 2008: e.T18232A7858611. http://dx.doi.org/10.2305/IUCN.UK.2008.RLTS.T18232A7858611.en

Mallon, D. & S. Kingswood. 2001. Antelopes. Part 4: North Africa, the Middle East and Asia. Global survey and regional action plans. IUCN SSC Antelope Specialist Group, Gland, Switzerland.

McGrath, F. Richter, R., Dugersuren, S, Yaylymova, A. 2011. Spirited Away – Mongolia's Mining Boom and the People that Development Left Behind. CEE Bank Watch Network. Prague, Czech Republic.

Mongolian Agency of Standardization and Meteorology. 2014. Mongolian State Standard for General Demands on Ungulates Crossing Across Highway and Railway (Draft).

Ministry of Transportation of Mongolia. 2014. Annual Traffic Count Report.

Mueller, S., and Berthoud, G. 1997. Fauna/traffic safety: manual for civil engineers. Ecole Polytechnique Federale de Lausanne, Department de genie civil. LAVOC, Lausanne, Switzerland.

Olson, K., T. Fuller, T. Mueller, M. Murray & C. Nicolson. 2010. Annual movements of Mongolian gazelles: nomads in the Eastern Steppe. Journal of Arid Environments 74: 1435-1442.

Olson, K., 2012. Wildlife Crossing Options Along Existing and Planned Mongolian Railway Corridors. Mongolian Discussion Papers, East Asia and Pacific Sustainable Development Department, Washington DC, World Bank.

Paige-Green, P. 1989. The Influence of Geotechnical Properties on the Performance of Gravel Wearing Course Materials. PhD Thesis. University of Pretoria, Pretoria, South Africa.

Papouchis, C.M., F.J. Singer & W.B. Sloan. 2001. Responses of desert bighorn sheep to increased human recreation. The Journal of Wildlife Management 65(3): 573-582.

Reading, R., H. Mix, B. Lkhagvasuren, C. Feh, D. Kane, S. Dulamtseren & S. Enkhbold. 2001. Status and distribution of khulan (Equus hemionus) in Mongolia. Journal of Zoology 254: 381-389.

Reading, R.P., S. Amgalanbaatar, G.J. Wingard, D. Kenny & A. DeNicola. 2005. Ecology of argali in Ikh Nartiin Chuluu, Dornogobi Aymag. Erforsch. biol. Ress. Mongolei (Halle/Saale) (9): 77-89.

Republic of South Africa Department of Transport. Draft TRH 20 Unsealed Roads: Design, Construction, and Maintenance . Technical Recommendations for Highways, Department of Transport, Republic of South Africa, Pretoria: Republic of South Africa, 2009.

Reynolds, H., Craighead, D., Proctor, M., Luvsamjamba, A., and Mijiddorj, B. Gobi Bear Conservation in Mongolia: Gobi Project Team Report. July 2010.

Sawyer H. & B. Rudd. 2005. Pronghorn roadway crossings: A review of available information and potential options. Western EcoSystems Technology, Inc., Cheyenne, Wyoming, USA. http://www.west-inc.com/reports/pronghorn_report_final.pdf

Seiler, A. 2005. Predicting Locations of Moose-Vehicle Collisions in Sweden. Journal of Applied Ecology. 42, 371-392.

Skorseth, K., and Selim, A.. Gravel Roads Maintenance and Design Manual. Federal Highway Administration, U.S. Department of Transporation, Brookings: South Dakota Local Transporation Assistance Program, 2000.

TBC and FFI, the Biodiversity Consultancy, Ltd. and Fauna & Flora International. 2011. Oyu Tolgoi Project, Biodiversity management plan: road upgrade to Gashuun Sukhait. Biodiversity Management Plan: Unpublished draft report of The Biodiversity Consultancy and Fauna & Flora International, July, 2011. Cambridge, UK.

Tsetsegmaa, L., 2004. The Silica Dust from the Enrich Mining Plant Infact to Motive the Endemic Disorders of Technopathic Origin in Livestock Population. Unpublished Dissertation. Mongolian State University of Agriculture, Ulaanbaatar.

Ukhaa Khudag. 2015. Ukhaa Hudag Environmental and Social Management Plan. Draft (unpublished) report.

von Wehrden H, Hanspach J, Ronnenberg K and Wesche K (2010) "Inter-annual rainfall variability in Central Asia – A contribution to the discussion on the importance of environmental stochasticity in drylands." Journal of Arid Environments 74(10): 1212-1215.

Watts, J. Gobi Mega-mine Puts Mongolia on Brink of World's Greatest Resource Boom. The Guardian November 7, 2011.

Walton, T. 2010. Southern Gobi Regional Environmental Assessment. Mongolia Discussion Papers, East Asia and Pacific Sustainable Development Department. Washington, D.C.: World Bank.

Yin, B. Z. Yu, S. Yang, H. Huai, Y. Zhang & W. Wei. 2007. Effects of Qinghai-Tibetan highway on the activities of Pantholops hodgsoni, Procapra picticaudata and Equus kiang. Shengtaixue Zazhi 26 (6): 810-816.

8. APPENDIX: UNPAVED ROAD CHEMICAL TREATMENTS

This appendix contains a summary of the origins, form supplied, attributes, limitations, application, and potential environmental impact for the various chemical treatment categories and sub-categories. It is copied with permission from Appendix A of Jones. (2013). Each topic is discussed in a separate table as follows:

- Table 1: Chemical treatment uses
- Table 2: Chemical treatment origins
- Table 3: Chemical treatment form of supply
- Table 4: Chemical treatment attributes
- Table 5: Chemical treatment application rates and methods
- Table 6: Chemical treatment environmental impacts
- Table 7: Chemical treatment limitations

The summary information provided in the tables is based on literature reviews and the experience of a panel of practitioners and should be updated as new information becomes available. This information should not be used as a sole basis for choice of chemical treatment, absolute determination of application rates, or for determining the potential level of environmental impact. Specific information, including proof of environmental testing, should always be requested from the chemical treatment supplier.

Table 1: Chemical Treatment Category Uses

Category	Sub-Category	Use
Water and water with surfactants	Water	▪ Short-term dust control
	Water with surfactant	▪ Short-term dust control
Water absorbing	Calcium chloride	▪ Fines preservation / dust control
	Magnesium chloride	▪ Fines preservation / dust control
	Sodium chloride	▪ Fines preservation / dust control
Organic non-petroleum	Glycerin/glyceride based	▪ Fines preservation / dust control
	Lignosulfonate	▪ Fines preservation / dust control
	Molasses/sugar	▪ Fines preservation / dust control
	Plant oil	▪ Fines preservation / dust control
	Tall oil pitch rosin	▪ Fines preservation / dust control
Organic petroleum	Asphalt emulsion	▪ Stabilization / all-weather passability ▪ Fines preservation / dust control
	Base and mineral oils	▪ Fines preservation / dust control
	Petroleum resin	▪ Fines preservation / dust control ▪ Stabilization / all-weather passability
	Synthetic fluid	▪ Fines preservation / dust control
	Synthetic fluid plus binder	▪ Fines preservation / dust control ▪ Stabilization / all-weather passability
Synthetic polymer emulsion	Typically polyvinyl acrylate, polyvinyl acetate, polyvinyl chlorate, or styrene-butadiene-styrene based	▪ Fines preservation / dust control ▪ Stabilization / all-weather passability
Concentrated liquid stabilizers	High acidity	▪ Stabilization / all-weather passability
	Low acidity/ Enzyme	▪ Stabilization / all-weather passability
Mechanical stabilization	Bentonite	▪ Mechanical stabilization ▪ Fines preservation / dust control

Table 2: Chemical Treatment Category Origins

The summary information provided in this table is based on literature reviews and the experience of a panel of practitioners and should be updated as new information becomes available. This information should not be used as a sole basis for choice of chemical treatment. Specific information should always be requested from the chemical treatment supplier.

Category	Sub-Category	Origin
Water and water with surfactants	Water	▪ Any water source ▪ May include contaminated water from industrial or mining processes/ operations
	Water with surfactant	▪ Any water source plus a surfactant to increase the "wetting ability" of the water ▪ Surfactants are typically soap based
Water absorbing	Calcium chloride	▪ Evaporated from naturally occurring brines (lake or sea water) ▪ By-product brine from the manufacture of sodium carbonate by ammonia-soda process or separation of bromine from natural brines ▪ Manufactured by neutralizing by-product hydrochloric acid (e.g., from sodium hydroxide production) with limestone or similar calcium source
	Magnesium chloride	▪ Evaporated from naturally occurring brines (lake or sea water)
	Sodium chloride brine	▪ Evaporated from naturally occurring brines (lake or sea water) ▪ Mined from rock salt
Organic non-petroleum	Glycerin/glyceride based	▪ By-product from plant oil and biofuel manufacturing ▪ Recycled from used cooking oil
	Lignosulfonate	▪ By-product from sulfite paper making process (i.e., Kraft process) ▪ Chemistry depends on extraction process chemicals (ammonium, calcium, or sodium) and to a certain extent tree species ▪ Performance depends on tree species ▪ Active constituent is neutralized sulfuric acid containing sugars
	Molasses/sugar	▪ By-product from the sugar cane and sugar beet processing industry
	Plant oil	▪ Manufactured as part of plant oil extraction ▪ Commonly used plants include soy, canola, sunflower, cotton, linseed, and palm
	Tall oil pitch rosin	▪ Distilled product from sulfite paper making process (i.e., Kraft process) ▪ Performance can depend on tree species
Organic petroleum	Asphalt emulsion	▪ Slow set asphalt (bitumen) emulsions, usually SS-1 (anionic) or CSS-1 (cationic) ▪ SS-1h and CSS-1h are not used unless a thicker crust/less penetration is required (e.g., very sandy soils) ▪ Cutback slow cure asphalt (bitumen) emulsions, usually SC-70, S-C250, or SC-800, are usually not used due to environmental limitations on volatiles
	Base and mineral oils	▪ Derived from crude oil in a physical separation process during refining ▪ Mineral oils can also be derived from industrial process by-products
	Petroleum resin	▪ Combination of petroleum resin derived from certain crude oil sources/ refining processes and lignin
	Synthetic fluid	▪ Manufactured specifically for dust control and surface stabilization from reaction products of specific chemical feedstock ▪ "Synthetic" is defined by EPA environmental regulatory testing requirements [40 CFR 435]
	Synthetic fluid plus binder	▪ Synthetic fluid together with binder from organic non-petroleum, organic petroleum, or synthetic polymer emulsion categories. Mix proportions will differ depending on objective
Synthetic polymer emulsion	Typically polyvinyl acrylate, polyvinyl acetate, polyvinyl chlorate, or styrene-butadiene-styrene based	▪ Manufactured specifically for dust control and surface stabilization to meet engineered specifications ▪ Can be by-product from adhesive or paint manufacturing processes
Concentrated liquid stabilizers	High acidity	▪ Proprietary sulfuric/phosphoric acid based products
	Low acidity/Enzyme	▪ Proprietary enzymatic protein based products
Mechanical stabilization	Bentonite	▪ Mined from natural clay deposits

Table 3: Chemical Treatment Form of Supply

Category	Sub-Category	Form of Supply
Water and water with surfactants	Water	▪ Liquid
	Water with surfactant	▪ Liquid ▪ Added surfactants can be liquid or powder ▪ Surfactant is usually highly concentrated
Water absorbing	Calcium chloride	▪ Liquid with 28 to 42% calcium chloride content, remainder water ▪ Flake with >75% calcium chloride content ▪ Pellet with > 94% calcium chloride content
	Magnesium chloride	▪ Liquid with 28 to 33% magnesium chloride content, remainder water
	Sodium chloride	▪ Liquid with varying quantities of sodium, magnesium, and calcium chloride, remainder water ▪ Salt crystals
Organic non-petroleum	Glycerin/glyceride based	▪ Liquid
	Lignosulfonate	▪ Liquid with >25% lignosulfonate content, remainder water ▪ Powder
	Molasses/sugar	▪ Liquid, active solids content varies depending on refining
	Plant oil	▪ Liquid, active solids content varies depending on refining
	Tall oil pitch rosin	▪ Liquid, active solids content varies depending on refining
Organic petroleum	Asphalt emulsion	▪ Liquid
	Base and mineral oils	▪ Liquid. Cannot be diluted with water
	Petroleum resin	▪ Liquid
	Synthetic fluid	▪ Liquid. Cannot be diluted with water
	Synthetic fluid plus binder	▪ Liquid. Cannot be diluted with water
Synthetic polymer emulsion	Typically polyvinyl acrylate, polyvinyl acetate, polyvinyl chlorate, or styrene-butadiene-styrene based	▪ Liquid ▪ Some products supplied as a powder, but not common
Concentrated liquid stabilizers	High acidity	▪ Liquid, highly concentrated
	Low acidity/ Enzyme	▪ Liquid, highly concentrated
Mechanical stabilization	Bentonite	▪ Powder

Table 4: Chemical Treatment Category Attributes

Category	Sub-Category	Attributes
Water and water with surfactants	Water	▪ Temporary agglomeration of the road material particles
	Water with surfactant	▪ Improved, but still temporary agglomeration of the road material particles
Water absorbing	Calcium chloride	▪ Hygroscopic[1], deliquescent[2], and exothermic[3] ▪ Agglomerates road material particles and holds them through surface tension ▪ Ability to absorb water is a function of temperature and relative humidity; for example, at 77°F (25°C) calcium chloride starts to absorb water from the air at 29% relative humidity and at 100°F (38°C) it starts to absorb water at 20% relative humidity ▪ Increases surface tension of water film between particles, helping to slow evaporation and further tighten compacted soil as drying progresses ▪ Increases dry strength of road material under dry conditions ▪ Does not reduce plasticity index or increase soaked shear strength (e.g., CBR), but can act as a compaction aid. ▪ Increases soil electrical conductivity (this can be used to track movement in the soil) ▪ Treated road can be bladed and recompacted after light watering with no or limited effect on performance
	Magnesium chloride	▪ Hygroscopic[1], deliquescent[2], and exothermic[3] ▪ Agglomerates road material particles and holds them through surface tension ▪ Absorbs water from the air at >30% relative humidity, independent of temperature ▪ Increases surface tension of water film between particles, helping to slow evaporation and further tighten compacted soil as drying progresses ▪ Increases dry strength of road material under dry conditions ▪ Does not reduce plasticity index or increase soaked shear strength (e.g., CBR), but can act as a compaction aid ▪ Increases soil electrical conductivity (this can be used to track movement in the soil) ▪ Treated road can be bladed and recompacted after light watering with no or limited effect on performance
	Sodium chloride brine	▪ Agglomerates road material particles and holds them through surface tension ▪ Water absorbing ability is dependent on percentages of magnesium, calcium, and sodium chloride ▪ Sodium chloride absorbs water from the air at 80% relative humidity independent of temperature ▪ Increases surface tension of water film between particles to a lesser degree than calcium and magnesium chloride ▪ Does not reduce plasticity index or increase soaked shear strength (e.g., CBR) ▪ Increases soil electrical conductivity (this can be used to track movement in the soil) ▪ Treated road can be bladed and recompacted after light watering with no or limited effect on performance

1 Hygroscopic: absorbs moisture from the air
2 Deliquescent: salt in solid form can dissolve into a liquid by absorbing atmospheric moisture
3 Exothermic: gives off heat as it dissolves from a solid to a liquid

(continued)

Category	Sub-Category	Attributes
Organic non-petroleum	Glycerin/glyceride based	▪ Usually combined with other organic non-petroleum binders ▪ Agglomerates road material particles through gluing and humectant (hygroscopic) properties. Duration/effectiveness is dependent on constituents ▪ Effective at very low temperatures ▪ Does not reduce plasticity index or increase soaked shear strength (e.g., CBR) unless mixed with other stabilization treatment ▪ Treated road can be bladed and recompacted after light watering with some effect on performance. May require retreatment after maintenance
	Lignosulfonate	▪ Lignins and complex carbohydrates glue road material particles together ▪ Retains effectiveness during long dry periods with low humidity ▪ Increases dry strength of road material under dry conditions ▪ Does not reduce plasticity index or increase soaked shear strength (e.g., CBR) ▪ Treated road can be bladed and recompacted after light watering with no or limited effect on performance
	Molasses/sugar	▪ Complex carbohydrates glue road material particles together providing temporary binding of the road surface particles ▪ Does not reduce plasticity index or increase soaked shear strength (e.g., CBR) ▪ Treated road can be bladed and recompacted after light watering with some effect on performance ▪ Typically requires retreatment after maintenance
	Plant oil	▪ Agglomerates road material particles ▪ Does not reduce plasticity index or increase soaked shear strength (e.g., CBR) ▪ Treated road can be bladed and recompacted after light watering with some effect on performance. May require retreatment after maintenance
	Tall oil pitch rosin	▪ Rosins glue road material particles together ▪ Retains effectiveness during long dry periods with low humidity ▪ Increases dry strength of road material under dry conditions ▪ Does not reduce plasticity index or increase soaked shear strength (e.g., CBR) ▪ Has better water resistance than other organic non-petroleum treatments ▪ Treated road can be bladed and recompacted after light watering with no or limited effect on performance
Organic petroleum	Asphalt emulsion	▪ Asphalt binds and agglomerates road material particles together ▪ Will reduce moisture sensitivity of material ▪ Increases soaked shear strength (e.g., CBR), but does not chemically reduce plasticity index ▪ Usually forms a crust on the surface of the road that cannot be maintained with a grader ▪ Requires reapplication after maintenance
	Base and mineral oils	▪ Agglomerates road material particles ▪ Retains effectiveness during long dry periods with low humidity ▪ Effective at low temperatures ▪ Does not reduce plasticity index or increase soaked shear strength (e.g., CBR) ▪ Treated road can be bladed and recompacted after light watering with no effect on performance
	Petroleum resin	▪ Agglomerates road material particles ▪ Will reduce moisture sensitivity of material ▪ Retains effectiveness during long dry periods with low humidity ▪ Increases soaked shear strength (e.g., CBR), but does not chemically reduce plasticity index ▪ Treated road can be bladed and recompacted after light watering with some effect on performance. Typically requires rejuvenation after maintenance

(continued)

Category	Sub-Category	Attributes
Organic petroleum	Synthetic fluid	▪ Agglomerates road material particles through cohesive binding mechanism ▪ Retains effectiveness during long dry periods with low humidity ▪ Retains effectiveness at extreme temperatures (hot or cold) ▪ Does not reduce plasticity index or increase soaked shear strength (e.g., CBR) ▪ Treated road can be bladed and recompacted after light watering with no or limited effect on performance
	Synthetic fluid plus binder	▪ Agglomerates road material particles through adhesive and cohesive binding mechanism ▪ Retains effectiveness during long dry periods with low humidity and in extreme temperatures (hot and cold) ▪ Increases dry strength of road material under dry conditions ▪ Does not reduce plasticity index but may increase soaked shear strength (e.g., CBR) depending on type of binder ▪ Treated road can be bladed and recompacted after light watering. Effect on performance depends on type of binder used
Synthetic polymer emulsion	Typically polyvinyl acrylate, polyvinyl acetate, polyvinyl chlorate, or styrene-butadiene-styrene based	▪ Binds surface particles through adhesive properties ▪ Retains effectiveness during long dry periods with low humidity ▪ Increases soaked shear strength (e.g., CBR) when mixed into material, but does not chemically reduce plasticity index ▪ Usually forms a crust on the surface of the road that cannot be maintained with a grader ▪ Requires reapplication after maintenance
Concentrated liquid stabilizers	High acidity	▪ Highly concentrated, therefore low transport costs ▪ Cation exchange alters clay mineral structure to reduce moisture sensitivity of the material ▪ Retains effectiveness during long dry periods with low humidity ▪ Effective compaction aid ▪ Increases soaked shear strength (e.g., CBR), but does not reduce plasticity index ▪ Treated road can be bladed and recompacted after light watering with little or no effect on performance
	Low acidity/enzyme	▪ Highly concentrated, therefore low transport costs ▪ Stabilization mechanism is not clearly understood, but protein molecules react with soil molecules to form a cementing bond that stabilizes the soil structure and reduces the soil's affinity for water ▪ Strength increases are often associated with compaction aid properties ▪ Does not reduce plasticity index ▪ Treated road can be bladed and recompacted after light watering with little or no effect on performance
Mechanical stabilization	Bentonite	▪ Clay is used to increase fines content of material and mechanically bind larger particles together to prevent washboarding and raveling ▪ Will increase plasticity index, but will not increase soaked shear strength (e.g., CBR) ▪ Treated road can be bladed and recompacted after light watering with little or no effect on performance

Table 5: Chemical Treatment Application Rates and Frequencies

The summary information provided in this table is based on literature reviews and the experience of a panel of practitioners and should be updated as new information becomes available. This information should not be used as a sole basis for absolute determination of application rates. Specific information should always be requested from the chemical treatment supplier. Supplied concentrations and recommended dilution rates should be fully understood to ensure that treatments from different distributors are compared fairly.

Category	Sub-Category	Typical Application Rate and Frequency
Water and water with surfactants	Water	▪ Spray-on application only ▪ Application rate depends on material properties, with higher rates on sandy materials ▪ Application frequency depends on temperature and humidity, but generally only effective for 0.5 to 12 hours
	Water with surfactant	▪ Spray-on application only ▪ Application rate depends on material properties, with higher rates on sandy materials ▪ Application frequency depends on temperature and humidity, but generally only effective for 0.5 to 12 hours
Water absorbing	Calcium chloride	▪ Spray-on or mix-in treatments. Mix-in will have longer effectiveness ▪ Initial application: - Liquid: 35 to 38% residual @ 0.2 to 0.35 g/yd^2 (0.9 to 1.6 L/m^2), typical application is 38% residual concentrate applied undiluted @ 0.35 g/yd^2 (1.6 L/m^2) - Flake: 1.0 to 2.0 lb./yd^2 (0.4 to 1.1 kg/m^2), typical application 1.7 lb./yd^2 (0.9 kg/m^2) @ 77% purity - Pellet: 1.0 to 1.8 lb./yd^2 (0.4 to 0.7 kg/m^2), typical application 1.4 lb./yd^2 (0.5 kg/m^2) @ 94% purity ▪ Spray-on applications are best applied in multiple light applications to assist penetration ▪ Rejuvenation is 50 to 70% of initial application rate ▪ Generally 1 to 2 treatments per season; first applied at end of wet or winter season
	Magnesium chloride	▪ Spray-on or mix-in treatments. Mix-in will have longer effectiveness ▪ Initial application is 28 to 35% residual @ 0.3 to 0.5 g/yd^2 (1.4 to 2.3 L/m^2), typical application is 30% residual concentrate applied undiluted @ 0.5 g/yd^2 (2.3 L/m^2) ▪ Spray-on applications are best applied in multiple light applications to assist penetration ▪ Rejuvenation is usually 50% of initial application rate ▪ Generally 1 to 2 treatments per season; first applied at end of wet or winter season
	Sodium chloride	▪ Usually spray-on treatments ▪ Application rate depends on calcium and magnesium chloride content ▪ Rejuvenation rate and interval dependent on calcium and magnesium chloride content
Organic non-petroleum	Glycerin/glyceride based	▪ Spray-on or mix-in treatments. Mix-in will have much longer effectiveness than spray-on treatment ▪ Initial application rate dependent on properties of glycerin and added binders, but typically 0.25 to 0.5 g/yd^2 (1.1 to 2.3 L/m^2) ▪ Spray-on applications are best applied in multiple light applications to assist penetration. Higher product temperatures improve penetration ▪ Rejuvenation is usually 50 to 70% of initial application rate ▪ Generally 1 to 2 treatments per season depending on temperature and humidity, with first applied at end of wet or winter season

(continued)

Category	Sub-Category	Typical Application Rate and Frequency
Organic non-petroleum	Lignosulfonate	▪ Spray-on or mix-in treatments. Mix-in will have much longer effectiveness than spray-on treatment ▪ Initial application rate dependent on lignosulfonate content: - 10 to 25% residual @ 0.5 to 1.0 g/yd^2 (2.3 to 4.5 L/m^2), typical application is 25% residual concentrate applied undiluted @ 0.5 g/yd^2 (2.3 L/m^2) - 50% residual applied diluted 1:1 with water @ 1.0 g/yd^2 (4.5 L/m^2) - Powder form mixed with water to give equivalent to 50% residual applied diluted 1:1 @ 1.0 g/yd^2 (4.5 L/m^2) ▪ Spray-on applications are best applied in multiple light applications to assist penetration ▪ Rejuvenation is usually 50 to 70% of initial application rate ▪ Generally 1 to 2 treatments per season, with first applied at end of wet or winter season
	Molasses/sugar	▪ Usually spray-on treatments ▪ Application rate depends on sugar content ▪ Rejuvenation rate and interval dependent on sugar content
	Plant oil	▪ Spray-on or mix-in treatments. Mix-in will have much longer effectiveness than spray-on treatment ▪ Initial application rate dependent on type of oil and oil content, but typically 0.25 to 0.5 g/yd^2 (1.1 to 2.3 L/m^2) ▪ Spray-on applications are best applied in multiple light applications to assist penetration. Higher product temperatures improve penetration ▪ Rejuvenation is usually 50 to 70% of initial application rate ▪ Generally 1 to 2 treatments per season; first applied at end of wet or winter season
	Tall oil pitch rosin	▪ Spray-on or mix-in treatments. Mix-in will have much longer effectiveness than spray-on treatment. Mix-in treatments must be used for stabilization ▪ Initial application rate dependent on rosin content: - 10 to 20% residual @ 0.3 to 1.0 g/yd^2 (1.4 to 4.5 L/m^2) - 40 to 50% residual applied diluted 1:4 with water @ 0.5 g/yd^2 (2.3 L/m^2) ▪ Spray-on applications are best applied in multiple light applications to assist penetration ▪ Rejuvenation is usually 50 to 70% of initial application rate ▪ Generally 1 treatment every 1 to 2 years
Organic petroleum	Asphalt emulsion	▪ Spray-on or mix-in treatments. Mix-in will have much longer effectiveness than spray-on treatment. Mix-in treatments must be used for stabilization ▪ Initial application rate typically 0.1 to 0.3 g/yd^2 (0.25 to 1.5 L/m^2) residual asphalt content ▪ Generally 1 treatment per season
	Base and mineral oils	▪ Usually spray-on treatment, but mix-in treatment will have longer period of effectiveness ▪ Initial application rate typically 0.33 g/yd^2 (1.5 L/m^2) ▪ Spray-on applications are best applied in 2 or 3 light applications to assist penetration. ▪ Rejuvenation is usually 50 to 70% of initial application rate ▪ Generally 1 to 2 treatments per season; first applied at end of wet or winter season
	Petroleum resin	▪ Spray-on or mix-in treatments. Mix-in will have much longer effectiveness than spray-on treatment. Mix-in treatments must be used for stabilization ▪ Initial application rate typically 0.11 to 0.55 g/yd^2 (0.5 to 2.5 L/m^2) depending on material properties ▪ Rejuvenation is usually 50 to 70% of initial application rate ▪ Generally 1 to 2 treatments per season; first applied at end of wet or winter season

(continued)

Category	Sub-Category	Typical Application Rate and Frequency
Organic petroleum	Synthetic fluid	▪ Usually spray-on treatment, but mix-in treatment will have longer period of effectiveness. Mix-in treatment must be used for stabilization. ▪ Initial application rate typically 0.22 g/yd^2 (1.1 L/m^2) ▪ Spray-on applications are best applied in 1 or 2 light applications to assist penetration. ▪ Rejuvenation is usually 50 to 70% of initial application rate ▪ Generally 1 to 2 treatments per season; first applied at end of wet or winter season
	Synthetic fluid plus binder	▪ Mix-in treatment for stabilization ▪ Initial application rate dependent on binder type and properties, and on intended outcome or engineering specification, but typically 0.22 g/yd^2 (1.0 L/m^2) ▪ Annual rejuvenation typically synthetic fluid plus binder applied at 0.11 to 0.17 g/yd^2 (0.5 to 0.75 L/m^2)
Synthetic polymer emulsion	Typically polyvinyl acrylate, polyvinyl acetate, polyvinyl chlorate, or styrene-butadiene-styrene based	▪ Spray-on or mix-in treatments. Spray-on treatments usually have limited effectiveness due to skin forming on surface. Mix-in treatments must be used for stabilization ▪ Initial application rate dependent on residual polymer content: - 5 to 15% residual @ 0.3 to 1.0 g/yd^2 (1.4 to 4.5 L/m^2) - 40 to 50% residual applied diluted 1:9 with water @ 0.5 g/yd^2 (2.3 L/m^2) ▪ Spray-on applications are best applied in multiple light, highly diluted applications to assist penetration ▪ Spray-on applications require reapplication after maintenance ▪ Rejuvenation on mix-in treatments is usually 50 to 80% of initial application rate ▪ Generally 1 to 2 treatments per season for spray-on treatments ▪ Generally 1 treatment per year for mix-in treatments
Concentrated liquid stabilizers	High acidity	▪ Mix-in treatments only ▪ Application rates typically vary between 0.01 and 0.03 L/m^2 (0.002 and 0.01 g/yd^2) ▪ Reaction is theoretically permanent so rejuvenation is not required
	Low acidity/ Enzyme	▪ Mix-in treatments only ▪ Application rates typically vary between 0.01 and 0.03 L/m^2 (0.002 and 0.01 g/yd^2) ▪ Reaction is theoretically permanent so rejuvenation is not required
Mechanical stabilization	Bentonite	▪ Mix-in treatments only ▪ Application rate dependent on material grading and plasticity index, with best results obtained when fines content after treatment is between 11 and 20 percent and plasticity index is between 6 and 10% (typically 1 to 3% bentonite by dry weight of aggregate) ▪ Rejuvenation is not required

Table 6: Chemical Treatment Environmental Impacts

The summary information provided in this table is based on literature reviews and the experience of a panel of practitioners and should be updated as new information becomes available. This information should not be used as a basis for absolute determination of the potential level of environmental impact. Proof of environmental testing should always be requested from the chemical treatment supplier.

Category	Sub-Category	Environmental Impacts
Water and water with surfactants	Water	▪ Depends on water source. Industrial water can have significant impacts ▪ Social impacts associated with using water that could otherwise be used for domestic or agricultural purposes
	Water with surfactant	▪ Depends on water source. Industrial water can have significant impacts ▪ Social impacts associated with using water that could otherwise be used for domestic or agricultural purposes ▪ Impacts to fresh water aquatic biota: when added to water or plant oils for dust control, may target gill tissue after spills/leaching into small streams
Water absorbing	Calcium chloride	▪ Considerable documented research and testing on environmental impacts ▪ Some impacts are confused with snow and ice control for which application rates are higher and application intervals more frequent ▪ Impacts to water quality: generally negligible if an appropriate buffer zone is maintained between road and water ▪ Impacts to fresh water aquatic biota: may develop at chloride concentrations as low as 400 ppm for trout and up to 10,000 ppm for other fish species ▪ Impacts to plants: some species may be susceptible such as pine, hemlock, poplar, ash, spruce, and maple ▪ Impacts to mammals: salt may attract animals to road ▪ Potential concerns with spills
	Magnesium chloride	▪ Considerable documented research and testing on environmental impacts ▪ Some impacts are confused with snow and ice control for which application rates are higher and application intervals more frequent ▪ Impacts to water quality: generally negligible if an appropriate buffer zone is maintained between road and water ▪ Impacts to fresh water aquatic biota: may develop at chloride concentrations as low as 400 ppm for trout and up to 10,000 ppm for other fish species ▪ Impacts to plants: some species may be susceptible such as pine, hemlock, poplar, ash, spruce, and maple ▪ Impacts to mammals: salt may attract animals to road ▪ Potential concerns with spills
	Sodium chloride	▪ Considerable documented research and testing on environmental impacts ▪ Some impacts are confused with snow and ice control for which application rates are higher and application intervals more frequent ▪ Impacts to water quality: generally negligible if an appropriate buffer zone is maintained between road and water ▪ Impacts to fresh water aquatic biota: may develop at chloride concentrations as low as 400 ppm for trout and up to 10,000 ppm for other fish species ▪ Impacts to plants: some species may be susceptible such as pine, hemlock, poplar, ash, spruce, and maple ▪ Impacts to mammals: salt may attract animals to road ▪ Potential concerns with spills
Organic non-petroleum	Glycerin/glyceride based	▪ Limited documented research on environmental impacts ▪ Impacts to water quality: none recorded ▪ Impacts to fresh water aquatic biota: none recorded ▪ Impacts to plants: none recorded ▪ Impacts to mammals: may attract animals to road ▪ Unrefined recycled food based glycerides may have unpleasant odor ▪ Potential concerns with spills

(continued)

Category	Sub-Category	Environmental Impacts
Organic non-petroleum	Lignosulfonate	▪ Considerable documented research and testing on environmental impacts ▪ Impacts to water quality: none recorded ▪ Impacts to fresh water aquatic biota: biological oxygen demand may be high after spills/leaching into small streams ▪ Impacts to plants: none expected ▪ Impacts to mammals: none expected ▪ Potential concern with spills
	Molasses/sugar	▪ Limited documented research on environmental impacts ▪ Impacts to water quality: unknown/none recorded ▪ Impacts to fresh water aquatic biota: biological oxygen demand may be high after spills/leaching into small streams ▪ Impacts to plants: unknown, none expected ▪ Impacts to mammals: animals and insects may be attracted to road ▪ Potential concern with spills
	Plant oil	▪ Limited documented research on environmental impacts ▪ Impacts to water quality: unknown/none recorded ▪ Impacts to fresh water aquatic biota: biological oxygen demand may be high after spills/leaching into small streams ▪ Impacts to plants: unknown, none expected ▪ Impacts to mammals: animals and insects may be attracted to road ▪ Potential concern with spills
	Tall oil pitch rosin	▪ Limited documented research on environmental impacts ▪ Impacts to water quality: unknown/none recorded ▪ Impacts to fresh water aquatic biota: biological oxygen demand may be high after spills/leaching into small streams ▪ Impacts to plants: unknown, none expected ▪ Impacts to mammals: unknown, none expected ▪ Potential concern with spills
Organic petroleum	Asphalt emulsion	▪ Considerable documented research and testing on environmental impacts ▪ Impacts to water quality: none after curing ▪ Impacts to fresh water aquatic biota: none after curing ▪ Impacts to plants: none provided no direct application ▪ Impacts to mammals: none after curing ▪ Cutbacks are not permitted in some areas due to impact of volatiles on air quality ▪ May have regulatory storage and reporting requirements ▪ Potential concern with spills
	Base and mineral oils	▪ Limited documented research on environmental impacts ▪ Impacts are dependent on specific product chemistry ▪ Chemical analysis and results of environmental testing from an accredited laboratory should be requested ▪ May have regulatory storage and reporting requirements ▪ Potential concern with spills and leaching prior to curing
	Petroleum resin	▪ Considerable documented research and testing on environmental impacts ▪ Impacts to water quality: none after curing ▪ Impacts to fresh water aquatic biota: none after curing. May be a concern if large volumes are spilled ▪ Impacts to plants: none provided no direct application ▪ Impacts to mammals: none after curing ▪ May have regulatory storage and reporting requirements ▪ Potential concern with spills

(continued)

Category	Sub-Category	Environmental Impacts
Organic petroleum	Synthetic fluid	▪ Must meet EPA environmental based criteria for synthetic (sediment toxicity, biodegradability, PAH content, aquatic toxicity, and oil sheen free) ▪ Impacts to water quality: none. May be a concern if large volumes are spilled ▪ Impacts to fresh water aquatic biota: none ▪ Impacts to plants: none ▪ Impacts to mammals: none ▪ Potential concerns with spills
	Synthetic fluid plus binder	▪ Impacts are dependent on specific binder chemistry but combination usually still meets EPA environmental based criteria for synthetic ▪ Impacts to water quality: none expected ▪ Impacts to fresh water aquatic biota: none expected ▪ Impacts to plants: none expected ▪ Impacts to mammals: none expected ▪ Potential concerns with spills
Synthetic polymer emulsion	Typically polyvinyl acrylate, polyvinyl acetate, polyvinyl chlorate, or styrene-butadiene-styrene based	▪ Limited documented research on environmental impacts ▪ Impacts are dependent on specific product chemistry ▪ Chemical analysis and results of environmental testing from an accredited laboratory should be requested ▪ Impacts to water quality: none expected. May be a concern if large volumes are spilled ▪ Impacts to fresh water aquatic biota: none expected ▪ Impacts to plants: none expected ▪ Impacts to mammals: none expected ▪ Potential concern with spills
Concentrated liquid stabilizers	High acidity	▪ Limited documented research on environmental impacts ▪ Impacts are dependent on specific product chemistry ▪ Chemical analysis and results of environmental testing from an accredited laboratory should be requested ▪ pH of undiluted product is very low ▪ Impacts to water quality: none expected. May be a concern if large volumes are spilled ▪ Impacts to fresh water aquatic biota: none expected ▪ Impacts to plants: none expected ▪ Impacts to mammals: none expected ▪ Potential concern with spills of concentrate
	Low acidity/ Enzyme	▪ Limited documented research on environmental impacts ▪ Impacts are dependent on specific product chemistry ▪ Chemical analysis and results of environmental testing from an accredited laboratory should be requested ▪ Impacts to water quality: none expected ▪ Impacts to fresh water aquatic biota: none expected ▪ Impacts to plants: none expected ▪ Impacts to mammals: none expected ▪ Potential concern with spills of concentrate
Mechanical stabilization	Bentonite	▪ Natural soil material ▪ Impacts to water quality: may increase sediment in water if erosion from road surface is not managed ▪ Impacts to fresh water aquatic biota: none expected ▪ Impacts to plants: none expected ▪ Impacts to mammals: none expected

Table 7: Chemical Treatment Limitations

The summary information provided in this table is based on literature reviews and the experience of a panel of practitioners and should be updated as new information becomes available. This information should not be used as a sole basis for choice of chemical treatment. Specific information should always be requested from the chemical treatment supplier.

Category	Sub-Category	Limitations
Water and water with surfactants	Water	▪ Short term dust control only, evaporates readily ▪ Generally the least cost-effective and most labor intensive form of dust control in the long term
	Water with surfactant	▪ Short term dust control only, evaporates readily, but some improvement compared to water only ▪ Generally the least cost-effective and most labor intensive form of dust control in the long term
Water absorbing	Calcium chloride	▪ Requires minimum humidity level to absorb moisture from the air ▪ Performs better than magnesium chloride when high humidity is present, but does not perform as well as magnesium chloride in long dry spells ▪ Slightly corrosive to metal, highly corrosive to aluminum and its alloys, attracts moisture thereby prolonging active period for corrosion ▪ Rainwater tends to leach out highly soluble chlorides ▪ Surface may become slippery when wet on materials with high fines content (>20% passing #200 [0.075 mm]) ▪ Solutions with <20% residual calcium chloride have similar performance to water spraying
	Magnesium chloride	▪ Requires minimum humidity level to absorb moisture from the air ▪ Corrosive to steel in concentrated solutions (some products may contain a corrosion-inhibiting additive), attracts moisture thereby prolonging active period for corrosion ▪ Rainwater tends to leach out highly soluble chlorides ▪ Surface may become slippery when wet on materials with high fines content (>20% passing #200 [0.075 mm]) ▪ Solutions with <20% residual magnesium chloride have similar performance to water spraying
	Sodium chloride	▪ Performance is dependent on calcium and magnesium content ▪ Calcium chloride and magnesium chloride provide better performance ▪ Requires minimum humidity level to absorb moisture from the air ▪ Corrosive to steel in concentrated solutions and moderately corrosive in dilute solutions ▪ Rainwater tends to leach out highly soluble chlorides ▪ Surface may become slippery when wet on materials with high fines content (>20% passing #200 [0.075 mm])
Organic non-petroleum	Glycerin/glyceride based	▪ Requires minimum humidity level to retain moisture in aggregate matrix ▪ Pricing closely linked to bio-diesel, grain, and competing markets, therefore volatile
	Lignosulfonate	▪ Performance varies depending on tree species, extraction process and level of refining (i.e., sugar content) ▪ Higher value competing markets may affect availability and product quality ▪ May cause corrosion of aluminum and its alloys ▪ Surface binding action may be reduced or completely destroyed by heavy rain, due to solubility of solids in water ▪ Surface may become slippery when wet on materials with high fines content (>20% passing #200 [0.075 mm]) ▪ Surface may become brittle during extended dry periods

(continued)

Category	Sub-Category	Limitations
Organic non-petroleum	Molasses/sugar	▪ Performance varies depending on extraction process and level of refining ▪ Limited period of effectiveness compared to other organic non-petroleum treatments ▪ Surface binding action may be reduced or completely destroyed by heavy rain, due to solubility of solids in water ▪ Surface may become slippery when wet on materials with high fines content (>20% passing #200 [0.075 mm]) ▪ Surface may become brittle during extended dry periods ▪ Generally only available in close proximity to sugar mills. Not cost-effective if transported long distances
	Plant oil	▪ Performance varies depending on extraction process and level of refining ▪ Can oxidize rapidly and become brittle ▪ Surface may become slippery when wet on materials with high fines content (>20% passing #200 [0.075 mm]) ▪ Higher value competing markets (e.g., food related) may affect availability and price
	Tall oil pitch rosin	▪ Performance varies depending on tree species, extraction process and level of refining ▪ Higher value competing markets may affect availability and product quality ▪ Surface binding action may be reduced by heavy rain, due to solubility of solids in water ▪ Surface may become brittle during extended dry periods
Organic petroleum	Asphalt emulsion	▪ Price directly linked to crude oil prices and therefore volatile ▪ Can oxidize rapidly and become brittle ▪ Difficult to maintain. Most treatments cannot be maintained with conventional unpaved road techniques ▪ Usually requires reapplication after maintenance ▪ May have regulatory storage and reporting requirements
	Base and mineral oils	▪ Wide variety of products available with performance dependent on chemistry and level of processing. Products from waste streams may have variable performance over time ▪ Price often linked to crude oil prices and therefore volatile ▪ May have regulatory storage and reporting requirements
	Petroleum resin	▪ Price often linked to crude oil prices and therefore volatile ▪ Surface may be difficult to maintain if thick, hard crust forms
	Synthetic fluid	▪ Price often linked to crude oil prices and therefore volatile
	Synthetic fluid plus binder	▪ Price often linked to crude oil prices and therefore volatile
Synthetic polymer emulsion	Typically polyvinyl acrylate, polyvinyl acetate, polyvinyl chlorate, or styrene-butadiene-styrene based	▪ Price often linked to crude oil prices and therefore volatile ▪ Wide variety of products available with performance dependent on source and level of processing. Products from waste streams may have variable performance over time ▪ Spray-on treatments usually have limited period of performance due to formation of skin or crust on the surface ▪ Can break down under ultra violet light ▪ Difficult to maintain. Most treatments cannot be maintained with conventional unpaved road techniques ▪ Usually requires reapplication after maintenance

(continued)

Category	Sub-Category	Limitations
Concentrated liquid stabilizers	High acidity	▪ Wide variety of products available ▪ Requires relatively high clay and fines content for satisfactory reaction to take place ▪ Performance is highly dependent on clay mineralogy of the material ▪ Actual stabilization mechanism is difficult to assess in a laboratory ▪ Period until stabilization (i.e., strength gain) has been achieved may be several months ▪ Product formulations are often changed to suit specific applications ▪ May require separate dust control treatment to prevent fines loss ▪ Limited independent scientific research to back up manufacturers claims
Concentrated liquid stabilizers	Low acidity/ Enzyme	▪ Wide variety of products available ▪ Requires relatively high clay and fines content for satisfactory reaction to take place ▪ Performance is highly dependent on mineralogy of the material ▪ Actual stabilization mechanism is difficult to assess in laboratory ▪ Period until stabilization (i.e., strength gain) has been achieved may be several months ▪ Product formulations are often changed to suit specific applications ▪ May require separate dust control treatment to prevent fines loss ▪ Limited independent scientific research to back up manufacturers claims
Mechanical stabilization	Bentonite	▪ Surface may become slippery if fines content and plasticity design limits are exceeded