NATURAL RISK ASSESSMENT IN CHILEAN ROAD NETWORK

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ABSTRACT

Chile is a country that year by year expenses a relevant part of national budget repairing damages in road network induced by natural disasters. Besides, very different natural hazards affect road network due to the big diversity of climatic and morphology areas of the country. Typical hazards existent in the country are river flooding due to *Invierno Altiplanico*, earthquakes, volcanic eruptions, landslides, flooding due to snowstorms. In addition, the country is highly vulnerable to the effects of El Niño and La Niña global climatic phenomena that cause intensive rains on winter and thaw on summer.

Because the country is long, tiny and mountainous, road network has an spatial configuration of a mixture of fishbone and fan, providing just a few alternative routes that cross numerous rivers, and increasing road vulnerability to natural hazards.

In the context of risk management, a relevant step is the assessment of risk because it permits to define target risk and mitigation measurements. The aim of this paper is to discuss the road risk index developed in Chile. The index is based is based on the concepts of exposition, vulnerability, strategic relevance of roads, roads hierarchy, accessibility, traffic level and existence of alternative routes.

The index was computed for Chilean roads with disruption records provided by the Chilean Highways Agency ranging between the years 1990 and 2009. A total of 799 roads were considered in the analysis. Risk index was categorized in three levels by means of clustering method and a ranking of roads that needs a more detailed assessment were identified. A complete database was designed and implemented in a Geographic Information System. It was concluded that the risk index developed is a useful tool for road planning and specifically for selecting roads that need immediate attention, more detailed studies or do nothing. In addition, the method provides general hints for including risk concepts in road assets management systems.

1. INTRODUCTION

Chile is a country that presents a variety of weather, morphology, and economic basis from north to south. Historically, this heterogeneity have marked the philosophy of road development, configuring a road network scheme as herringbone organized around routes 5, 7 and 9 and lateral roads with just specific areas in which road network offers alternatives roads and connectivity with similar standards.

This condition determines a high vulnerability to natural hazards that are diverse too due to the nearby to Andean Mountains, Nazca Plates, Altiplane and Patagonic glaciers. Also, Chile is a country very sensitivity to global weather activity (El Niño and La Niña mainly), that joined to seismic activity, volcanic activity, altiplanic winter, and patagonic weather, comprise many efforts of national highways agency to maintain the network level of service. This effort translates in a relevant part of sectorial budget to repair roads disrupted by natural events previously depicted.

This situation, encourage to the National Highways Agency through its Road Planning Department to develop a study for characterizing and assessing risk in national road network, with exception of concessed road. Into this framework, the authors develop the methodology for rating risk presented in this paper, based in previous experience existent en Chile in bridge maintenance management planning. One of the premises of the methodology was that should be easy to use, that input data should easy to obtain without detailed field work and based on databases of national highways agency. This premises and restrains were accomplished totally.

Several authors had developed rapid assessment methods in different fields, being more popular in public health studies, environmental impact assessment, and rural areas planning among others. In transportation engineering, research have focused in the analysis of vulnerability of road networks and the effects of natural and anthropic hazards, and risk analysis (Keller, 2002; Rowshan et al, 2003; Xia et al, 2005; Husdal, 2005 y 2006; Taylor et al, 2006; Susilawati and Taylor, 2007; Erath et al, 2009).

Particularly Xia et al (2005) developed a method based on a risk index, which is estimated by using semantic scales that qualify road attributes like traffic, road hierarchy, alternative routes among others. Research of Xia et al (2005) and of Valenzuela et al (2010) is the main reference considered in the research developed in this paper.

This paper have the objective of present one of the results of a research conducted in Chile to identify, prioritizes and recommend roads with high risk of disruption under the basis of a rapid estimation of risk levels.

The paper starts with a general framework of the methodology developed, followed by a detailed explanation of the equation and scales used to estimate a risk index. Next, a discussion of the application performed in the Chilean road network except concessed roads. Finally conclusions and recommendations are presented.

2. ASSESSMENT METHOD FOR RISK ESTIMATION

2.1. General Framework

The model is based on the usual concept of risk, that correspond of the product of occurrence probability of natural event and the consequences for the population (or nature) (Berdica, 2002; Jenelius et al, 2006; Free et al, 2006; Hall et al, 2006; Murray et al, 2008; Valenzuela et al, 2010).

The method is based in three concepts: First geo-hazards management of Free et al (2006), who developed a management system for vital networks. Second, methodological framework provided by Xia (2005), Jelenius et al (2006) and Murray et al (2008) who explains the concepts of risk, occurrence probability and consequences of total or partial interruption of road networks. Third, the integration of vulnerability and risk of road network developed by Valenzuela et al (2010) and applied to road bridges.

Considering these concepts, several equations to configure a risk index were developed. Coefficients were obtained by sceneries simulation of all possible combinations of parameters (2^{15}). One of the main requirements was that the method should be easy to use and that the input data were the lowest. The architecture of the method is showed in Figure 1.

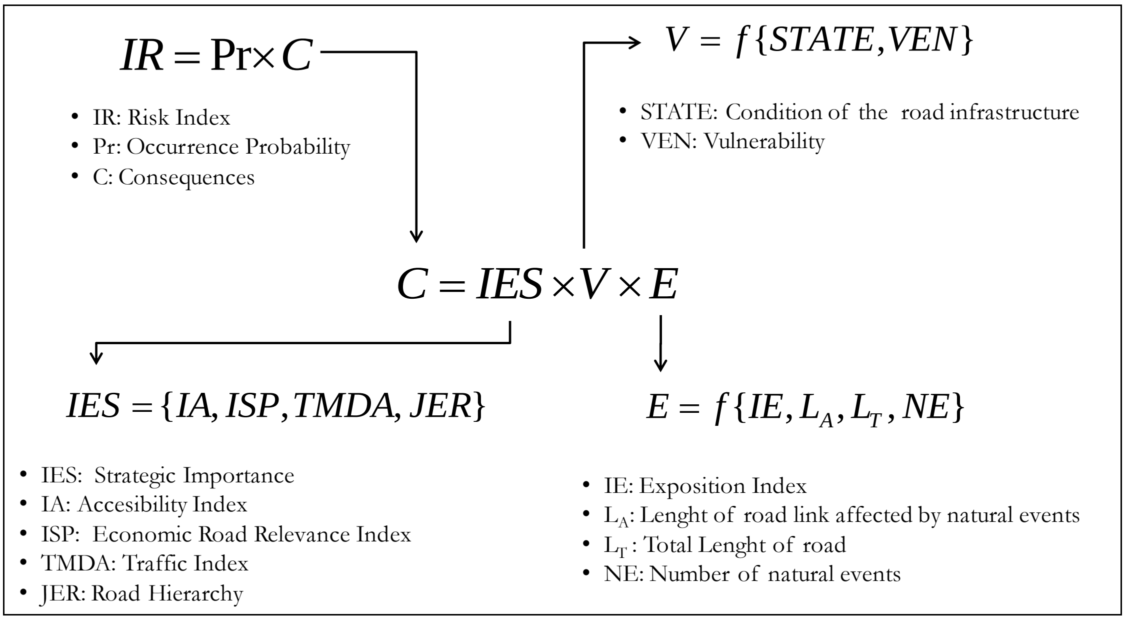

Figure 1 - General Framework of the method for Assessing Risk in Road Network.

Figure 1 shows that Risk Index can be estimated if occurrence probability and consequences are known. Consequences are estimated by knowing strategic importance of the road, its vulnerability and its exposure to natural hazards. Vulnerability is function of infrastructure conditions and failure probability that are properties defined from engineering design. Finally, strategic importance is dependant of the context in which road is placed.

The method can be used for different purposes: For instance for rank network or sub-networks according to the level of risk. This rank permits to prioritize mitigations and abatement action to reduce risk index. Also, permits to identify areas vulnerable to certain natural hazards and focus the investments. Particularly, in this paper the focus of the discussion is how to obtain a ranking of roads according to the level of risk in all the macro zones of the country.

2.2. Risk Concept

The basic concept of the method is risk. Operatively risk is the product of the occurrence probability and the consequences over the population (Free et al, 2006). Occurrence probability is the frequency in which natural events happens. For instance, of hydrological event is considered, occurrence probability is the period of return. Consequences are the impacts on the population induced by the natural event. These can be measured by estimating strategic importance of the road network, its vulnerability and its exposure to natural risk. The last three concepts are studied in detail in the following sections.

2.2.1. *Risk Index*

Risk index (IR) is a non-dimensional number estimated by using Eq. 1 (Ryall, 2001; p 413 – 418), where Pr is the occurrence probability and C are the consequences.

$$IR = Pr \times C \qquad (1)$$

2.2.2. *Probability of Occurrence*

It is defined as the frequency with natural events take place. It is particular for each type of natural hazard and is related to the geographic characteristics of the country. Table 1 shows the semantic scale that permits to assign a value to the variable Pr.

Table 1 - Semantic Scale for Valuation of Occurrence Probability (Pr)

Pr	Description	
0,01 - 0,1	Very Low	Phenomenon or hazard is not frequent. Is unusual in the influence area and have a return period higher than 200 years.
0,1 - 0,4	Low	Phenomenon or hazard has low frequency. Its return period is higher than 50 years and lower than 200 years.
0,4 - 0,7	Medium	Phenomenon or hazard is recurrent and its return period ranges between 10 and 50 years.
0,7 - 1,0	High	Phenomenon is highly repetitive. It has a return period ranging between 1 and 10 years.

2.2.3. *Consequences*

This parameter is the product of strategic importance (IES), vulnerability (V) and exposure (E), as show Eq. 2. All these parameters are non-dimensional.

$$C = IES \times V \times E \qquad (2)$$

2.3. Vulnerability

Vulnerability is related to the general condition of road, its structures, drainage system, slopes and lateral areas. This general condition establishes the resistance of road to natural hazards and is dependant of the engineering design. According to Valenzuela et al (2010), vulnerability is the weighed sum of the road condition, the potential damage induced by floods, slope sliding.

Mathematical expression of vulnerability (V) is showed in Eq. 3, in which STATE represent the general condition of road and VEN is a vulnerability index of the natural event class "J". V ranges between 1 and 5. V=1 means low vulnerability and V=5 means high vulnerability.

$$V = 0{,}1 + 0{,}44(STATE) + 0{,}53\left\{\frac{1}{N}\sum_{J=1}^{N} VEN_J\right\} \quad (3)$$

2.3.1. *Estimation of STATE index*

Road with highly deteriorated condition are more susceptible to natural hazards. Table 2 was built under the basis if this assumption

Table 2 - Semantic scale to qualify STATE index

Road Condition	STATE Index	Description
Good	1	Paved Roads: Pavement good, embankment and slopes and drainage system has good condition.
	2	Unpaved Roads: roadway surface good, embankment and slopes and drainage system has good condition.
Regular	3	Roadway is slightly rough. Embankment and slopes has erosion evidences, drainage system is deteriorated and shows evidence of local erosion.
Bad	4	Roadway is highly rough. Embankment and slopes has erosion evidences, drainage system is deteriorated and shows local erosion.
Very Bad	5	Roadway is highly deteriorated. Embankment and slopes has erosion and gullies. Drainage systems do not exist or is destroyed and obstructed by debris. Local erosion is evident.

In a road link, its vulnerability is related to the bridge or culverts density measured as bridges or culverts per km. Also, is related to the generalized bridge condition. At planning level and in cases in which detailed inventory don´t exist, bridge density can be valued in levels high, medium and low. Bridge and culvert condition is obtained by using segmental visual inspection or from database of maintenance units of highways agencies (Dirección de Vialidad 2010a y 2010b; Valenzuela et al, 2010).

Once bridge density and condition is obtained, the rules for assessment are:

- If bridge density is medium or high and bridge condition is bad, add 1 to scale of Table 2.
- If culvert condition is high and its generalized condition is bad or have erosion symptoms, add 1 to scale of Table 2.
- Otherwise, obtain the STATE variable directly from Table 2.

2.3.2. *Vulnerability Index (VEN).*

This index explains the potential damage on road infrastructure due to a natural event. Tables 3 and 4 shows VEN index values for floods and for sliding, respectively. If bridge density is high, add 1 level to index of Table 3. If culverts density is high, add 1 level to the index obtained from Table 4. Is recommended that the qualification of each vulnerability level be performed by an specialist in hydraulic and geotechnics.

Table 3 – Vulnerability Index for Floods

VEN Index	Vulnerability Level	
1	None	Failure probability is lowest or null
2	Low	Failure probability of road and its structures due to floods and /or scour is low.
3	Medium	Is probable that road and its infrastructures fails due to floods and scour
4	High	Failure Probability of road infrastructure, drainage systems and / or complementary hardware and structures is high, due to flood and scour.
5	Very High	Road and its complementary are endangered. Collapse risk is high.

Table 4 – Vulnerability Index for Slope Sliding

VEN Index	Vulnerability Level	
1	None	Failure probability is lowest or null
2	Low	Failure probability of road and its structures due to slopes displacement is low.
3	Medium	Is probable that road and its infrastructures fails due to slope displacements induced by persistent not intense rain
4	High	Failure Probability of road infrastructure, drainage systems and / or complementary hardware and structures is high, due to slopes displacements due to persistent and intense rain
5	Very High	Road infrastructure, complementary elements have a very high failure probability

2.3.3. *Effect of Type of road surface on Vulnerability*

Gravel and earth road are more susceptibility to surface erosion due to rain or floods. In this cases, it is recommended to correct vulnerability estimated with Eq. 3 by adding 0,5 point.

2.4. Strategic Importance

Strategic importance of road is explained trough its relationship and interaction with and within the economic activities system, with the others links of the road network. Is strongly dependant of the presence/absence of alternative routes between nodes (towns, cities industrial clusters, etc.). In addition, if traffic levels are high, it is expected that strategic importance will be high too. Valenzuela et al (2010), defines strategic importance by using Eq. 4, in which accessibility, economic activity, traffic levels and road hierarchy are the explanatory variable

$$IES = 0,05 + 0,28(IA) + 0,22(ISP) + 0,23(TMDA) + 0,25(JER) \qquad (4)$$

Where:

- IES: Strategic Importance, non-dimensional
- IA: Accessibility Index, non-dimensional
- ISP: Economic Road Relevance Index, non-dimensional
- TMDA: Traffic Index, non-dimensional
- JER: Road Hierarchy Index, non-dimensional

2.4.1. *Accessibility Index*

This index considers the availability of two or more similar roads between two origin / destiny nodes. If exist just one road, strategic importance rise. Otherwise, decrease. Table 5 shows the valuation of different levels of accessibility. It was based on Wardrop's equilibrium, which establish that the route choice is dependent on the operating cost and travel time that road user perceive for each alternative.

Table 5 – Accessibility Index Valuation

Accessibility Level	Accessibility Index	Description
High	1	Alternatives road between origins and destinies are competitive and operating costs and travel time are similar.
Regular	2	There exist alternative roads. Operating cost and tim travel cost are slightly higher in comparison to the studied road.
Medium	3	There exist alternative roads but operating costs and time travel cost is high. Standard of alternative road is low in comparison to the road studied.
Low	4	Alternative roads have load restrains on bridges. Standard of alternative road is low and eventually unpaved.
Null	5	Alternatives do not exist

2.4.2. *Economic Road Relevance Index*

This index describes the relevance of road for economic activity in its influence area. in Chile, economic activities have specific and non-competitive locations for each relevant economic activity. Strategic importance of road is related to the size of the economic activity. For instance, mining is relevant in north zone of Chile and is not relevant in the south.

Table 6 - Valuation of Economic Road Relevance Index (Valenzuela et al, 2010).

Macro zone	ISP Values	Economic Activity
North	5	Mining
	3	Farming, fishery
	1	Other
Center	5	Industry, winery and farming
	3	Mining and fishery
	1	Other
South	5	Farming and forestry
	3	Livestock and aquaculture
	1	Other
Patagonia	5	Fishery and aquaculture
	3	Forestry and energy production
	1	Other

2.4.3. *Traffic Index*

This index explains how traffic levels modify strategic importance of a certain road. If traffic index is high, strategic importance is high too.

For estimating traffic levels data of a traffic study that covered national road network performed by the National Highways Agency was used. On each macro zone, traffic data were clustered to obtain traffic levels by using k-mean clustering method. Table 7 shows results obtained.

Table 7 - Traffic index for each macro zone, according to traffic levels

Macro Zone	Traffic Level	Traffic Range (veh/day - year)	Traffic Index
North	Low	<1.200	1
	Medium	1.200 a 5.000	3
	High	>5.000	5
Center	Low	<6.600	1
	Medium	6.600 a 31.800	3
	High	>31.800	5
South	Low	<1.800	1
	Medium	1.800 a 6.700	3
	High	>6.700	5
Patagonia	Low	<620	1
	Medium	620 a 3.300	3
	High	>3.300	5

2.4.4. *Road Hierarchy Index*

This index explains the relevance of the route in the context of the transportation system. According to national act N° 566 of the Ministry of Public Works of Chile, Chilean roads are classified as international, national, regional and local roads. This classification was adopted in Table 8 to elaborate Road Hierarchy Index (JER).

Table 8 – Road Hierarchy Index according to road functionality

Road Hierarchy	JER Index
International and National roads with high mobility levels	>4, ≤ 5
Connecting regional roads with high mobility	>3, ≤ 4
Regional and local roads which its primary objective is accessibility to isolated territories	>3, ≤ 4
Regional and local roads, which its primary objective is access to isolated territories. These territories have optional means for connectivity.	>2, ≤ 3
Very local road which its principal objective is local accessibility	≤ 2

2.5. Exposure Index

Exposure to risk is a measurement f the historical natural events that affect the entire road or a segment. Index proposed considered Chilean record of natural events that disrupts roads in the last 20 years. Road with recurrent history of disruption had high exposure to risk. Because the origin of natural hazards on each macro zone is different, we consider proper to classify exposure index for each macro zone. Table 9 shows the exposure index as function of exposure values estimated by using Eq. 5.

Table 9 – IE range of values for each macro-zone and Exposure Index valuation

Exposure Index (E)	Exposure Value (IE)			
	North	Center	South	Patagonia
1	0 - 2	0 - 5	0 - 2	0 - 2
3	2 - 8	5 - 20	2 - 10	2 - 20
5	Higher than 8	Higher than 20	Higher than 10	Higher than 20

$$IE = \left(\frac{L_A}{L_T} \right) NE \qquad (5)$$

Where:

IE: Exposure Index, non-dimensional
$L_{A:}$ Average length of the route affected by historical natural events, Km
L_T: Total length of road or link, Km
NE: total number of natural events on the time-period under analysis

3. ASSESSMENT OF NATIONAL ROAD NETWORK

Method depicted in previous sections was applied to the national road network of Chile, excluding concessed highways. National road network is composed of a 22 % of paved roads and 88 % of unpaved roads with a length of 78.000 Km. A detailed statistic of disruption in road network due to natural events was used as a basis of diagnosis. Data considers records from 1990 to 2009. 30.000 Km of roads in which at least one record of disruption were chosen.

A database that includes, road code, segment, length and type of pavement surface was configures. We group this database in four macro-zones: North, Center, South and Patagonia. Boundaries of macro zones were defined considering the nature and territorial extension of natural hazards. For instance, north consider altiplanic rains as the main natural hazard that occurs in summer. In contrast, Patagonia considers rains, river floods and snow that are concentrated mainly in winter as the main natural hazard.

After that, several characteristics needed as inputs for computing IR were collected. Road characteristics were obtained from the National Road Inventory, traffic data (composition, growth rate, AADT) were obtained from the National Traffic Survey (Direccion de Vialidad, 1994 – 2008; Dirección de Vialidad 2007) and Infrastructure condition was obtained from the Department of Highways Management of the National Highways Agency of the Ministry of Public Works.

Table 10 summarized roads categorized by macro zone and risk index level (IR) levels for the 800 roads studied. Risks levels were obtained after the estimation or risk index by clustering in three levels (high, medium and low) separately for each macro zone. K-means clustering tool was used for this purpose because its simplicity.

Table 11 shows a sample of Arica and Parinacota region, located in North macro zone.

Table 11 shows that two roads have risk level high. Both roads exhibit high vulnerability, high exposure to risk and the highest risk index. It implies that for a planning point of view that need immediate adoption of mitigation measures for reducing its vulnerability.

Table 10 - Risk condition of road network analyzed.

Macro zone	High	Medium	Low	Total
North	12	25	55	92
Center	12	174	180	366
South	12	28	235	275
Patagonia	2	5	60	67
Country	38	232	530	800

Table 11 – Example of Risk Index Calculation: Arica and Parinacota Region

Route code	Strategic Importance (IES)	Vulnerability (V)	Exposition (E)	Risk Index	Risk Level
A-302	3,1	2,5	1	7,1	Low
A-127	2,5	2,5	1	5,8	Low
A-201	2,3	2,5	3	15,4	Low
A-307	3,1	3,2	3	26,3	Medium
A-319	2,1	2,7	1	5,1	Low
A-323	3,1	3,0	1	8,3	Medium
Route 5	4,5	1,9	1	5,9	Low
A-23	3,1	2,8	5	38,6	Low
A-235	2,8	2,8	3	21,3	Low
A-345	3,1	3,0	5	41,4	Medium
A-93	3,3	3,2	3	29,3	Medium
A-331	3,1	2,7	3	22,7	Low
A-15	3,3	3,5	5	52,8	High
A-27	3,5	1,6	3	15,2	Low
A-35	3,3	2,6	1	7,7	Low
Route 11	3,5	3,0	5	47,7	High

After calculation of IR, a ranking was elaborated for selecting roads that need immediate attention or the need of more detailed studies. Only road with highest risk levels on each region were selected. Table 12 shows the results of this calculation.

Table 12 – Routes in which risk index obtained was high according to each macro zone and region.

Macro Zone	Region	Route	IR
North	Arica and Parinacota	A-15	52,8
		Route 11-CH	47,7
	Antofagasta	Route 1	41,0
		Route 21-CH	41,0
		Route 23-CH	41,0
		B-207	29,0
		Route 27-CH	27,0
	Atacama	Route 31-CH	46,3
		Route 5	39,0
		C-35	36,6
		C-17	30,0
Center	Valparaíso	Route 68	34,7
		F-30-E	31,0
		F-800	24,4
	Metropolitana	G-25	50,0
		G-421	27,0
		G-21	32,0
		G-251	25,0
		G-355	20,0
	O'Higgins	H-448	32,0
		H-328	23,0
	Maule	J-60	28,0
		M-50	27,0
South	Bio Bio	O-14	35,0
	La Araucanía	R-22	27,0
		R-89	27,0
		R-35	25,0
	Los Ríos	T-350	33,4
		Route 201-CH	25,2
		T-393	23,6
		T-270	20,8
	Los Lagos – North	Route 225-CH	56,0
		U-69	41,0
		U-40	34,0
		U-30	23,0
Patagonia	Los Lagos – South	Route 7	77,0
		Route 235-CH	75,0
	Aysén	Route 7	41,0
		X-25	36,0

4. CONCLUSIONS

Rapid assessment is a suitable tool to rate the risk of road at a network level. The method proposed, is focused on this purpose: Considering the history of disruption of the road network, to estimate a risk index and identify the roads that needs mitigation measurement to keep its level of service over the minimum value.

The method is based on simple equations that were calibrated by using sceneries simulation and considering earlier jobs developed in Chile, regarded with bridge maintenance. Now, authors are applying a Delphi-based calibration to estimate with more accuracy the parameters of equation that describes strategic importance.

The method was applied to the complete Chilean road network. Considering the history of road disruption and characteristics of natural hazards, a sample of 800 roads (30.000 Km) were considered to identify roads that need mitigation and improvements. From these roads approximately 38 were rated with high risk, 253 with medium risk and 530 with low risk.

A relevant property of the method is that input data are easy to obtain. Many of it are year by year surveyed and recorded in highways agencies.

Chilean weather, morphology and characteristics of road network, are heterogeneous. Hence, the method was applied on macro zones that are independent one of each other. Into each macro zone, risks index was classified in levels by applying cluster method.

Results obtained were satisfactory, considering that, all the road with higher risk index were coincident with those that local roads authorities assign high strategic importance, vulnerability and risk exposure.

Further research is needed to estimate vulnerability more accurately. Authors are working in to obtain with help of expert panel a vulnerability function of embankments and slopes in roads based on visual inspection, similarly to the methodology developed by Valenzuela et al. At the same time, method should be implement in a GIS that will incorporate standardized records of road emergencies and disruptions, a core database of road infrastructure and traffic, and the risks index formulation. Now a day the research team of this project is working on this task.

Another relevant aspect is the task once roads are rated with risk index high, is necessary to assess the social benefits (or des-benefit) of mitigate by reducing road vulnerability versus road clearance with machinery year by year. This valuation should consider characteristics of road network near to the studied road and the social cost of operate with load, geometric or operating restrains during a year.

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