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EFFECT OF CLIMATE CHANGE ON CANADIAN BRIDGE INFRASTRUCTURES

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Abstract: The transportation networks, especially bridge infrastructures, can be considered as one of the most systems that will be affected by changing climate. The service life of such infrastructures is typically in the order of the time frame of the expected climate change scenarios (50 to 100 years). Several design parameters are considered in the bridge standards that depends either directly or indirectly on the climatic data, including: temperature, relative humidity, ice accretion, wind, and water loads. It should be pointed out that all these climatic parameters have been derived from historical data that goes back to the 1970's time horizon. Thus, the existing and future infrastructures might face higher extreme climatic events than loads considered in the current practices. This paper investigates the applicability of the current design climate loads of the Canadian Highway Bridge Design Code (CHBDC) to model current and future climatic actions. The studied climate loads include: daily temperatures (maximum, and minimum), relative humidity, and hourly mean wind pressures (for return periods of 50 and 100 years). The climatic design loads of CHBDC are compared with the current loads estimated based on homogenized climatic data from Environment Canada's national archives. Nineteen cities are selected based on the population density and to include all climatic regions, three largest cities, the national capital, and all provincial and territorial capitals. The results showed that, the CHBDC climate parameters are in need to be revised and/or projected to reflect the future climate changes for most Canadian climatic regions.

Keywords: Climate change; Bridge infrastructure; daily temperature; relative humidity; wind pressure.

1 INTRODUCTION

There is growing awareness worldwide that climate change will have significant impacts on the resilience of infrastructure, especially transportation networks. The frequency and/or the intensity of extreme weather events are now obvious. Global temperatures increased by more than 1°C leading to the melting of the ice-pack at the North Pole (IPCC 2014). The pattern, intensity and frequency of both precipitation and hurricanes have been changed dramatically over the last few years. These changes are substantially significant in higher-latitude regions, such as Canada and Eurasia, compared to the rest of the world. Currently, Alaska and Arctic regions are already seeing the early effects of global climate change on infrastructure. Permafrost melting due to relatively high temperature in Alaska and Northern Canada has resulted in heaving, thawing, sinkholes and settlement issues, all of which are affecting roads, bridges, and railways (Larsen et al. 2008). Additionally, Canada experienced several extreme events in 2017. This year was the eighth warmest period in 70 years of reporting weather, with temperatures averaging increase by 1.4°C above normal. Table 1 provides a summary of 2017's severe weather events in

Canada (excluding drought) and their impacts on infrastructure and community, along with estimated costs (Environment Canada 2018). Furthermore, Climate researchers expect future climate change in Canada and other Arctic places to be more pronounced than it is elsewhere in the world.

Table 1: A list of recorded extreme climate events that occurred over 2017 in Canada

Climate Event	Description	Damage/Loss	Estimated Cost (Million CAD)
Newfoundland's Brier blast (March 1 to 10)	- The strongest in a decade. - Hurricane-force winds ravaged Newfoundland with an extreme of 190 km/h at Bay de Verde.	Winds pulled out/blew away: - Traffic lights and power lines - Houses roofs (4,500 claims)	Insurance payouts ≈ $60
The storm of the century (March 13 to 15)	- Worst storm across Eastern Canada - Winds reaching 175 km/h caused total whiteouts - Over a metre of snow in Quebec.	- 5 dead - Hundreds of serious injuries - Over 50 cars and 15 trucks accident in whiteout conditions - Officials closed the 401	
Spring flooding in Quebec and Ontario (May1 to 7)	The worst ever recorded since 1870s	- 5,000 residences were flooded - Over 15,750 damaged property - Over 550 roads were washed	Insurance payouts ≈ $223
Windsor flood (August 28 to 31)	- Two storms of the century in a year - The wettest Summer in Eastern Canadian history - Most expensive single-storm loss across Canada in 2017	- Water filled thousands of basements and streets	Insurance payouts ≈ $154
British Columbia's wildfire season (July 7 to September 15)	Longest and most destructive wildfire season in the province's history	Fires burned: - Over 300 structures - Hundreds of power poles and transmission towers - 1.2 million hectares of timber	- Firefighting cost > $500. - Insured property ≈ $130. - Infrastructure ≈ $80.

In general, the effect of climate change are widespread throughout the world and are difficult to quantify. This paper focuses mainly on integrating the climate change impacts in the design of highway bridge infrastructure in Canada. Based on the literature and aforementioned evidences, it is clear that actions are needed at a number of levels to address, mitigate and consider the climate change impacts on the planning, design, construction and maintenance of key infrastructure. A great deal of research on managing climate risk has been conducted in recent years. Most of these studies have focused on reducing (i.e., mitigating) the greenhouse gas emissions (GHG) that spurring climate change. However, latest scientific studies have concluded that the climate change will continue for several decades, regardless of the level of success in reducing GHG emissions because of the existing cumulative concentration of GHG in the atmosphere (NRC 2007; Meyer, Asce, and Weigel 2011). Another stream of research places more emphasis on analyzing and estimating the cost of the potential damage in critical infrastructure that might be caused by climate change. Ultimately, few studies have suggested risk-based approaches to assess when climate adoption becomes economically viable (Stewart and Deng 2015; Larsen et al. 2008). In summary, all these studies have concluded that future climate changes may lead to different climatic loads on infrastructure, which in turn will lead to reduced safety, loss of serviceability, shortened service life, long service disruption, high rehabilitation and replacement costs, and significant negative socio-economic impacts. Additionally, the transportation system (bridges, roads, railways, etc.) and marine infrastructure are the most sectors that will face significant impacts of the climate change (Meyer, Asce, and Weigel 2011). While a great amount of research has been done, most of these studies are nascent, quantitative in nature, and serve as a stimulus for further discussions around climate change risk and adaptation. Very little research has been conducted to date on how climate change could influence the design loads and structural capacity of the infrastructure. The development of new design guidelines and/or approaches is still in early stages around the world.

This paper investigates the applicability of the current design climate loads of the Canadian Highway Bridge Design Code (CHBDC) to model current and future Canadian climatic actions. The studied climate loads include: daily temperatures (maximum, minimum, and mean), relative humidity, and hourly mean wind pressures (for return periods of 25, 50 and 100 years). The climatic design loads of CHBDC are compared with the current loads estimated based on homogenized climatic data from Environment Canada's national archives for twenty main Canadian cities.

2 CLIMATIC REGIONS AND CLIMATE CHANGE IN CANADA

Canada is the second largest country in the world with a landmass area of approximately 10 million km^2. For this reason, Canada is the land of many climates (refer to, Figure 1) including maritime, continental, arctic climates. The general characteristics of different climate regions in Canada are summarized in Table 2. The weather and climate of Canada vary greatly spatially across provinces and temporally from one season to the other. Additionally, the population of Canada is concentrated in the south in proximity to the border with the U.S. The geographical and socioeconomic diversity of Canada makes it difficult to generalize or represent the climate change impacts for the entire country, and regional climatic data must be used to analyze the climate change effects.

Figure 1: Canadian climate regions (Environment Canada 2018)

Table 2: General Characteristics of Climate Regions in Canada

Region	Climatic Characteristics
Pacific: maritime climate	Summer: cool, moderately humid, Winter: mild, cloudy, wet. This region is rainier than any other in Canada.
Cordilleran: variable	Summer: hot, dry in south, cooler, wetter in North Winter: milder than summer in South, more precipitation in North Daily temperature variations are greater than anywhere else in Canada.
Prairie: continental climate	Summer: short, warm/hot, low precipitation, high humidity Winter: very cold winters Extreme differences between summer and winter temperatures
Great Lakes/St. Lawrence: continental climate modified by Great Lakes in the west	Summer: Quite Warm, heavier precipitation Winter: short, heavier precipitation.
Atlantic: continental climate	Summer: short, mild, lots of precipitation Winter: cold, lots of precipitation (heavier compared to Summer)
Boreal	Cool, dry
Arctic	Cold, dry, permafrost region

Since 1950 the annual average surface air temperature over Canada's landmass has warmed by 1.7°C, and average temperatures in Canada are expected to rise spatially by an additional 1.5 ^{o}C – 4.5 ^{o}C by 2100. A summary of annual mean temperature and linear trends for the globe, all of Canada, southern Canada (i.e., south of 60°N), and northern Canada (i.e., north of 60°N) are shown in Figure 2. It is obvious that the rate of warming in Canada as a whole has been approximately twice the global average, and that warming rate in northern Canada is more pronounced and has been roughly three times the global average (Environment and Climate Change Canada, 2016). As warm air can hold more moisture, more precipitation events may occur as local temperatures rise, with intense precipitation and flooding expected to occur more frequently and with greater severity. Canada has, in general, become wetter in recent decades particularly the North. Annual precipitation between 1948 to 2005 has increased throughout the north with the largest increases over Arctic tundra (+25%) and Arctic mountain (+16%) regions. On the other hand, most of the country (particularly the southern Prairies and northeastern Ontario) have experienced an insignificant increase in annual precipitation (Environment and Climate Change Canada, 2016).

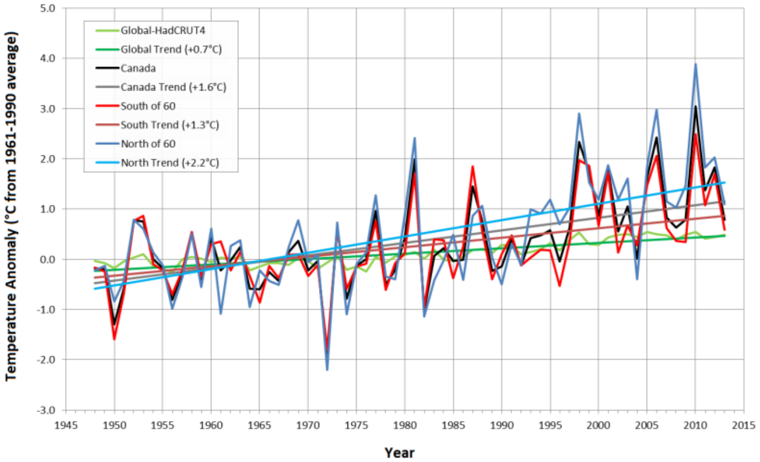

Figure 2: Annual mean temperatures and linear trends relative to 1961–1990 Canadian average (Environment and Climate Change Canada, 2016)

3 DESIGN PRACTICES ACCORDING TO CHBDC (CAN/CSA-S6-14)

Like all design standards, the current Canadian Highway Bridge Design Code (CHBDC) (CSA-S6 2014) specifies several design parameters that are depend either directly or indirectly on climatic data, such as temperature, relative humidity, ice accretion, ice load, wind, and water loads. Climate change therefore may have consequences on the design of new bridges, as well as the resistance in the existing infrastructure. However, there is no significant updates have been made in design standards to integrate future climate loads. Table 3 summarizes the sources of climatic baseline data used in the current CHBDC. As reported, most current design climatic parameters are derived from historical data that goes back to 1960 horizon (CSA-S6 2014). This means that the structural safety of new infrastructure that designed using current standards may be at risk in the future considering the climate change impacts.

Table 3: Sources of climatic and environmental data of CHBDC

Design parameter	Climatic baseline description	References (Measurements source)
Temperature	Maximum and minimum mean daily air temperatures Values are based on 30-year records up to 1970.	Fig. A3.1.1 and A3.1.2 (Environment Canada 1975)
Relative humidity	Annual mean relative humidity Values are based 10 years data (1957-1966)	Fig. A3.1.3 (Environment Canada 1968)
Ice accretion	Values are based on 20-year return period	Fig. A3.1.4 (Environment Canada 1974)
Wind	Hourly mean reference wind pressure for 600 locations for return periods of 10, 25, 50, 100 years.	Annex A3.1 Table A3.1.1 (NBCC 1990)

In the following subsections, the applicability of the current design climate loads of CHBDC to model current and future climatic actions is investigated. To examine the reliability of climate data of CHBDC code, the design values are compared to the data from Environment Canada measurements up to 2018 at the local level. The cities are selected based on the population density and to include all climatic regions, the three largest cities, the national capital, and all provincial and territorial capitals.

3.1 Temperature

Figure 3 presents the maximum and minimum mean daily bridge effective temperatures, respectively. As mentioned before these data are based on the climatic database that returns back to 1975 (CSA-S6 2014). To examine the applicability of temperature extremes provided by CHBDC to calculate thermal effects of current and future infrastructure, Table 4 provides a comparison between the temperature date provided by CHBDC (CSA-S6 2014) and temperature data processed from Environment Canada's national archives for 19 selected Canadian. The actual temperature data are processed following the same method reported in CHBDC commentary (CSA-S6 2014). Maximum and minimum mean daily air temperatures for a period of 30 years are used to construct Table 4. The mean temperature on a particular day has been taken as the average of the highest and lowest temperatures recorded on that day. The only difference between CHBDC data and processed data is the time period. The code values are based on temperature measurements from 1940-1970 period, while the processed data are estimated using latest measurements (i.e., based on 1988-2018 time period).

The comparison of results indicated reasonable consistency between the temperature data from the isotherms provided by CHBDC and the latest Environment Canada data. Therefore, existing temperature data of CHBDC are reasonably reflective of the updated temperature observations up to 2018 for all climate regions except northern Canada (i.e., north of 60°N). As highlighted in Table 4, the maximum and minimum mean daily temperatures for this region are warmer than the design values by 3°C in average. This conclusion is consistent with the predicted projection of future temperature in Northern Canada reported in (Environment and Climate Change Canada 2016) (refer to, Figure 2)

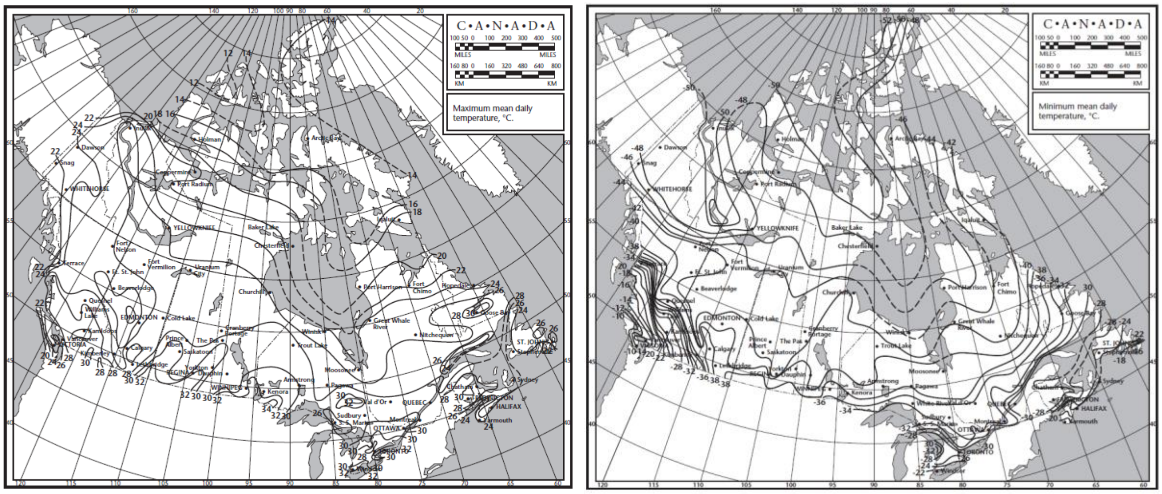

Figure 3: Design mean daily temperatures (left: Maximum; right: Minimum) (CSA-S6 2014)

Table 4: Comparison between temperature data provided by CHBDC and recent measurement

Data Base		CHBDC (1940-1970)		Env. Canada (1988-2018)	
Climate region	City, PE	Min	Max	Min	Max
Great lakes	Ottawa, ON	-30	+30	-29.9	+29.7
	Toronto, ON	-28	+32	-27.3	+31.9
	Montreal, QC	-34	+30	-32.2	+30.2
	Quebec, QC	-29	+29	-30.1	+29.2
Atlantic	Fredericton, NB	-29	+29	-26.6	+27.9
	Halifax, NS	-22	+26	-22.5	+27.5
	St. Johns, NL	-23	+25	-22.4	+24.2
Prairies	Regina, SK	-38	+32	-35.3	+29.6
	Winnipeg, MB	-37	+31	-35.2	+29.8
	Calgary, AB	-37	+28	-36.7	+26.5
	Edmonton, AB	-41	+26	-37.8	+25.1
Pacific	Vancouver, BC	-15	+28	-11.8	+27.4
	Victoria, BC	-14	+25	-10.5	+25.3
Yukon	Whitehorse, YT	-47	+23	**-45.2**	**+26.4**
	Dawson, YT	-49	+24	**-47.1**	**+27.9**
Mackenzie	Yellowknife, NT	-46	+26	**-43.2**	**+28.5**
	Norman, NT	-50	+22	**-47.5**	**+25.0**
Arctic	Iqaluit, NU	-42	+18	**-38.5**	**+21.1**
	Arctic Bay, NU	-47	+14.5	**-43.2**	**+17.3**

3.2 Relative humidity

In general, annual average relative humidity is used for estimating the shrinkage and creep losses for pre-stressed concrete members. Relative humidity is defined as the vapour pressure of the air expressed as a percentage of the saturation vapour pressure of the air at the same temperature. According to CHBDC commentary (CSA-S6 2014), the annual average relative humidity is estimated as the arithmetic average of the monthly average relative humidities for the decade of 1957 to 1966, inclusive. Figure 4 shows iso-lines of annual average relative humidity used by CHBDC for estimating the shrinkage and creep losses for pre-stressed concrete members.

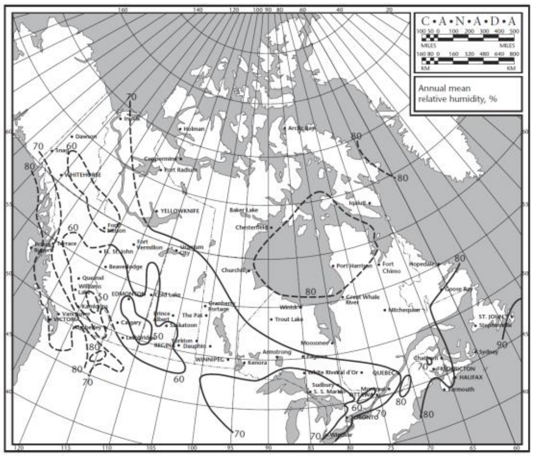

Figure 4: Annual mean relative humidity (Figure A3.1.3-(CSA-S6 2014))

Table 5 provides a comparison between the monthly average relative humidities date provided by CHBDC (CSA-S6 2014) and values estimated based on recent data from Environment Canada's national archives for the 19 selected Canadian. The actual relative humidity data are processed following the same method reported in CHBDC commentary (CSA-S6 2014). It is obvious from Table 5 that the southern Canada (Great lakes, Prairies, Pacific climate regions) experience significant higher relative humidity values than that provided by CHBC (CSA-S6 2014).

Table 5: Comparison between relative humidity provided by CHBDC and recent measurements

Data Base		Relative humidity (%)	
Climate region	City, PE	CHBDC (1957-1966)	Env. Canada (2009-2018)
Great lakes	Ottawa, ON	65	**75**
	Toronto, ON	70	72
	Montreal, QC	65	**73**
	Quebec, QC	70	**74**
Atlantic	Fredericton, NB	75	77
	Halifax, NS	80	82
	St. Johns, NL	85	87
Prairies	Regina, SK	60	**77**
	Winnipeg, MB	65	**77**
	Calgary, AB	55	**66**
	Edmonton, AB	50	**73**
Pacific	Vancouver, BC	75	**82**
	Victoria, BC	80	81
Yukon	Whitehorse, YT	68	70
	Dawson, YT	65	66
Mackenzie	Yellowknife, NT	72	72
	Norman, NT	68	74
Arctic	Iqaluit, NU	80	82
	Arctic Bay, NU	80	77

3.3 Wind

The CHBDC considers wind load forces on all three directions in the space. Such wind loads depend directly on the hourly mean reference wind pressure (q), which in turn depends on the local reference wind speed (V). According to CHBDC commentary (CSA-S6 2014), the hourly mean reference wind pressures are based on values extracted from The national building code (NBCC) 1990. The NBCC reports that the reference wind pressure (q) is estimated based on mean wind speed (V) using the following formula:

[1] $q = CV^2$

Where: the factor C depends on atmospheric pressure and air temperature. The NBCC uses $C = 50 \times 10^{-6}$ for V in km/h, which means NBCC adopts air density of 1.29 kg/m³. It should be pointed out that reference wind speed is a measure of the hourly mean wind speed taken at sites (usually airports) chosen in most cases to be representative of a height of 10 m in an open exposure. This is determined by extreme value analysis of meteorological observations of hourly mean wind speeds.

The CHBDC (CSA-S6 2014) provides the hourly mean reference wind pressure (q) in Appendix A4.1 based on the type and span of the bridge. Two different return periods of hourly mean reference wind pressures (q) are considered for structural elements: 100 years return period for bridge structures with any span 125 m long or longer; and 50 years return periods for bridge structures with a maximum span shorter than 125 m. Table 6 provides a comparison between the reference wind pressure data provided by CHBDC (CSA-S6 2014) and pressures estimated based on wind speed data from Environment Canada's national archives for the 19 selected Canadian. The actual wind pressure data are processed following the same method and return periods reported in code commentary(CSA-S6 2014). The comparison of wind pressures indicated reasonable consistency between the data from the Table A4.1provided by CHBDC and the latest Environment Canada data up to 2018 for most climate regions. The comparison indicates that the Atlantic climate region experiences high wind pressures that adapt by CHBDC.

Table 6: Comparison between reference wind pressure provided by CHBDC and pressures evaluated based on recent wind speed measurement

Data Base		CHBDC		Environment Canada			
Climate region	City, PE	q_{50} (Pa)	q_{100} (Pa)	V_{50} (km/h)	q_{50} (Pa)	V_{100} (km/h)	q_{100} (Pa)
Great lakes	Ottawa, ON	410	460	74	274	80	320
	Toronto, ON	520	580	85	361	97	470
	Montreal, QC	400	440	83	344	90	405
	Quebec, QC	520	580	130	**845**	130	**845**
Atlantic	Fredericton, NB	410	460	80	320	80	320
	Halifax, NS	590	670	113	**638**	113	638
	St. Johns, NL	800	890	120	720	137	**938**
Prairies	Regina, SK	420	460	89	396	97	470
	Winnipeg, MB	450	490	87	378	89	396
	Calgary, AB	495	540	93	432	93	432
	Edmonton, AB	450	510	69	238	72	259
Pacific	Vancouver, BC	480	530	82	336	89	396
	Victoria, BC	630	690	67	224	77	296
Yukon	Whitehorse, YT	370	420	72	259	72	259
	Dawson, YT*	310	340	46	106	46	106
Mackenzie	Yellowknife, NT	470	530	72	259	72	259
	Norman, NT	665	790	74	274	80	320
Arctic	Iqaluit, NU	750	840	111	616	129	832
	Arctic Bay, NU*	550	620	93	432	93	432

4 CONCLUSIONS

The current Canadian Highway Bridge Design Code (CSA-S6 2014), like all design standards, specifies several design parameters that are depend on climatic data, such as temperature, relative humidity, ice accretion, ice load, wind, and water loads. Climate change therefore may have consequences on the design of new bridges, as well as the resistance in the existing infrastructure. Most current design climatic parameters used on CHBDC are derived from historical data that goes back to 1960 horizon (CSA-S6 2014). This means that the structural safety of new infrastructure that designed using current standards may be at risk in the future considering the climate change impacts.

In this study, the applicability of the current design climate loads of CHBDC to model current and future climatic actions is investigated. The climate data of CHBDC code are compared to the data from Environment Canada measurements up to 2018 at the local level. Nineteen cities are selected based on the population density and to include all climatic regions, three largest cities, the national capital, and all provincial and territorial capitals. In general, the climate loads that in use by CHBDC are in need to be revised and/or projected to reflect the future climate changes. The following conclusions highlight the regions with an urgent need to update climate loads:

1. The comparison of temperature data indicated reasonable consistency between the isotherms provided by CHBDC and the latest Environment Canada data up to 2018 except for Northern Canada (i.e., north of 60°N). Maximum and minimum mean daily air temperatures that are based on Environment Canada measurements are higher in average by 3^{o}C than the values provided by CHBDC. However,

2. The comparison between the monthly average relative humidities date provided by CHBDC and values estimated based on recent data from Environment Canada showed that the southern Canada (Great Lakes, Prairies, Pacific climate regions) experience significant higher relative humidity values than that provided by CHBDC.

3. The comparison between the reference wind pressure date provided by CHBDC and pressures estimated based on wind speed data from Environment Canada’s national archives indicates that the Atlantic climate region experiences high wind pressures that adapt by CHBDC.

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