Supplementary Materials: The Role of Rail Transit Systems in Reducing Energy and Carbon Dioxide Emissions: The Case of The City of Rio de Janeiro

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All calculations were done with Microsoft Excel. Due to rounding, numbers presented in this text can be somewhat different from those calculated in the spreadsheets.

All references in this text also appear in the main text and in the reference list.

All supplementary informations are related to Rio de Janeiro Metro Line 4 in the period: second half of 2016 to 2040. All equations referenced are described in the main text.

1. Transport Performance of L4

1.1. O-D Matrix: Distance in Kilometers between Line 4 Metro Stations. Source: Flores [1]

Table S1. O-D Matrix: Distance in Kilometers between Line 4 Metro Stations. Source: Flores [1].

	JOC	SCO	ATQ	JAL	NSP	GOS	GAV	L1-L2
JOC	-	6.108	9.428	10.2	11.265	12.339	11.732	12.339
SCO	6.108	-	3.32	4.092	5.157	6.231	5.624	6.31
ATQ	9.428	3.32	-	0.772	1.837	2.911	2.304	2.911
JAL	10.2	4.092	0.772	-	1.065	2.139	3.076	2.139
NSP	11.265	5.157	1.837	1.065	-	1.074	4.141	1.074
GOS	12.339	6.231	2.911	2.139	1.074	-	5.215	-
GAV	11.732	5.624	2.304	3.076	4.141	5.215	-	5.215
L1-L2	12.339	6.231	2.911	2.139	1.074	-	5.215	-

Stations: JOC = Jardim Oceânico; SCO = São Conrado; ATQ = Antero de Quental; JAL = Jardim de Alah; NSP = N. Sa. da Paz; GOS = General Osório; GAV = Gávea; L1-L2 = Lines 1 or 2.

e.g., the distance from JOC to NSP is 11.265 km.

1.2. O-D Matrix: Passengers Traveling–Three Morning Peak Hours on Business Days-2016. Source: FGV [2]

Table S2. O-D Matrix: Passengers Traveling–Three Morning Peak Hours on Business Days-2016. Source: FGV [2].

	JOC	SCO	ATQ	JAL	NSP	GOS	GAV	L1-L2	TOTAL
JOC	-	2635	1933	966	2459	1050	1846	19,654	30,543
SCO	2748	-	2205	910	558	1195	979	6093	14,688
ATQ	924	2386	-	235	538	270	138	1988	6479
JAL	418	839	90	-	160	202	52	1633	3394
NSP	410	480	515	129	-	1119	38	2819	5510
GOS	504	1067	514	387	4495	-	123	-	7090
GAV	929	712	179	51	701	277	-	601	3450
L1-L2	4523	4745	3908	2817	6546	-	1978	-	24,517
TOTAL	10,456	12,864	9344	5495	15,457	4113	5154	32,788	95,671

e.g., 30,543 passengers embarked in JOC. 2459 of these passengers disembarked in NSP.

1.3. O-D Matrix: Passenger Kilometer (PKM)–Three Morning Peak Hours on Business Days-2016. (By Applying Equation (1))

Table S3. O-D Matrix: Passenger Kilometer (PKM)–Three Morning Peak Hours on Business Days-2016.

	JOC	SCO	ATQ	JAL	NSP	GOS	GAV	L1-L2	TOTAL
JOC	-	16,095	18,224	9853	27,701	12,956	21,657	242,511	348,997
SCO	16,785	-	7321	3724	2878	7446	5506	37,965	81,624
ATQ	8711	7922	-	181	988	786	318	5787	24,694
JAL	4264	3433	69	-	170	432	160	3493	12,022
NSP	4619	2475	946	137	-	1202	157	3028	12,564
GOS	6219	6648	1496	828	4828	-	641	-	20,660
GAV	10,899	4004	412	157	2903	1445	-	3134	22,954
L1-L2	55,809	29,566	11,376	6026	7030	-	10,315	-	120,123
TOTAL	107,306	70,144	39,845	20,906	46,498	24,266	38,755	295,918	**643,638**

e.g., the passengers who embarked in JOC and disembarked in NSP were responsible for:
11.265 km × 2459 passengers = 27,701 PKM.
The total PKM for three morning peak hours in 2016 is 643,638 km.

1.4. O-D Matrix: Passengers Traveling–Three Morning Peak Hours on Business Days-2026. Source: FGV [2]

Table S4. O-D Matrix: Passengers Traveling–Three Morning Peak Hours on Business Days-2026. Source: FGV [2].

	JOC	SCO	ATQ	JAL	NSP	GOS	GAV	L1-L2	TOTAL
JOC	-	4044	2915	1427	3651	1583	2564	29,018	45,202
SCO	4186	-	3359	1382	844	1810	1353	9243	22,177
LEB	921	2408	-	234	536	269	125	1980	6473
JDA	415	843	89	-	159	201	47	1628	3382
NSP	494	580	623	156	-	1361	42	3397	6653
IGO	589	1246	604	449	5451	-	131	-	8470
GAV	863	665	167	47	654	258	-	557	3211
L1-L2	4983	4730	4132	2906	6655	-	1791	-	25,197
TOTAL	12,451	14,516	11,889	6601	17,950	5482	6053	45,823	120,765

1.5. O-D Matrix: PKM–Three Morning Peak Hours on Business Days-2026. (By Applying Equation (1))

Table S5. O-D Matrix: PKM–Three Morning Peak Hours on Business Days-2026.

	JOC	SCO	ATQ	JAL	NSP	GOS	GAV	L1-L2	TOTAL
JOC	-	24,701	27,483	14,555	41,129	19,533	30,081	358,053	515,534
SCO	25,568	-	11,152	5655	4353	11,278	7609	57,593	123,208
LEB	8683	7995	-	181	985	783	288	5764	24,678
JDA	4233	3450	69	-	169	430	145	3482	11,977
NSP	5565	2991	1144	166	-	1462	174	3648	15,151
IGO	7268	7764	1758	960	5854	-	683	-	24,288
GAV	10,125	3740	385	145	2708	1345	-	2905	21,352
L1-L2	61,485	29,473	12,028	6216	7147	-	9340	-	125,690
TOTAL	122,927	80,112	54,019	27,878	62,345	34,831	48,320	431,445	**861,878**

1.6. O-D Matrix: Passengers Traveling–Three Morning Peak Hours on Business Days-2036. Source: FGV [2]

Table S6. O-D Matrix: Passengers Traveling–Three Morning Peak Hours on Business Days-2036.

	JOC	**SCO**	**ATQ**	**JAL**	**NSP**	**GOS**	**GAV**	**L1-L2**	**TOTAL**
JOC	-	3360	2997	1225	3077	1332	2607	41,353	55,951
SCO	5973	-	3535	1321	779	1645	1440	9864	24,557
LEB	1505	2381	-	208	535	263	144	2696	7732
JDA	664	807	87	-	160	186	53	2202	4159
NSP	692	452	622	154	-	1154	42	4287	7403
IGO	1015	1223	716	473	5908	-	166	-	9501
GAV	1209	547	173	47	580	223	-	669	3448
L1-L2	7117	4910	4453	2671	7253	-	2147	-	28,551
TOTAL	18,175	13,680	12,583	6099	18,292	4803	6599	61,071	141,302

1.7. O-D Matrix: PKM–Three Morning Peak Hours on Business Days-2036. (By Applying Equation (1))

Table S7. O-D Matrix: PKM–Three Morning Peak Hours on Business Days-2036.

	JOC	**SCO**	**ATQ**	**JAL**	**NSP**	**GOS**	**GAV**	**L1-L2**	**TOTAL**
JOC	-	20,523	28,256	12,495	34,662	16,436	30,585	510,255	653,212
SCO	36,483	-	11,736	5406	4017	10,250	8099	61,463	137,453
LEB	14,189	7905	-	161	983	766	332	7848	32,183
JDA	6773	3302	67	-	170	398	163	4710	15,584
NSP	7795	2331	1143	164	0	1239	174	4604	17,451
IGO	12,524	7621	2084	1012	6345	-	866	-	30,452
GAV	14,184	3076	399	145	2402	1163	-	3489	24,857
L1-L2	87,817	30,594	12,963	5713	7790	-	11,197	-	156,073
TOTAL	179,765	75,352	56,647	25,095	56,370	30,251	51,415	592,368	**1,067,263**

1.8. O-D Matrix: Passengers Traveling–Three Morning Peak Hours on Business Days-2040. Source: FGV [2]

Table S8. O-D Matrix: Passengers Traveling–Three Morning Peak Hours on Business Days-2040.

	JOC	**SCO**	**ATQ**	**JAL**	**NSP**	**GOS**	**GAV**	**L1-L2**	**TOTAL**
JOC	-	3025	3018	1147	2861	1230	2613	47,462	61,356
SCO	6571	-	3681	1323	780	1604	1513	9944	25,416
LEB	1831	2340	-	198	534	259	152	3079	8393
JDA	801	783	86	-	160	179	56	2486	4551
NSP	791	405	622	153	-	1073	42	4755	7841
IGO	1253	1190	761	480	6059	-	181	-	9924
GAV	1384	499	175	47	553	209	-	727	3594
L1-L2	8194	4867	4552	2563	7447	-	2292	-	29,915
TOTAL	20,825	13,109	12,895	5911	18,394	4554	6849	68,453	150,990

1.9. O-D Matrix: PKM–Three Morning Peak Hours on Business Days-2040. (By Applying Equation (1))

Table S9. O-D Matrix: PKM–Three Morning Peak Hours on Business Days-2040.

	JOC	SCO	LEB	JDA	NSP	GOS	GAV	L1-L2	TOTAL
JOC	-	18,477	28,454	11,699	32,229	15,177	30,656	585,634	722,325
SCO	40,136	0	12,221	5414	4022	9995	8509	61,961	142,257
LEB	17,263	7769	-	153	981	754	350	8963	36,232
JDA	8170	3204	66	0	170	383	172	5318	17,484
NSP	8911	2089	1143	163	-	1152	174	5107	18,738
IGO	15,461	7415	2215	1027	6507	0	944	-	33,569
GAV	16,237	2806	403	145	2290	1090	-	3791	26,762
L1-L2	101,106	30,326	13,251	5482	7998	-	11,953	-	170,116
TOTAL	207,283	72,086	57,753	24,082	54,198	28,551	52,758	670,773	**1,167,484**

1.10. PKM on Business Days

PKM of morning peak on business days = 20.70% of PKM on business day as observed in other lines [1].

PKM on business days will be:

2016: 643,638/20.70% = 3,109,362.

2026: 861,878/20.70% = 4,163,660.

2036: 1,067,263/20.70% = 5,155,862.

2040: 1,167,484/20.70% = 5,640,020.

1.11. PKM on Saturdays, Sundays and Holidays

As observed in other lines PKM on Saturdays, Sundays and holidays are, respectively, 39%, 21% and 23% of business day [1].

PKM on Saturdays will be:

2016: 3,109,362 × 39% = 1,212,651.

2026: 4,163,660 × 39% = 1,623,827.

2036: 5,155,862 × 39% = 2,010,786.

2040: 5,640,020 × 39% = 2,199,608.

PKM on Sundays will be:

2016: 3,109,362 × 21% = 652,966.

2026: 4,163,660 × 21% = 874,369.

2036: 5,155,862 × 21% = 1,082,731.

2040: 5,640,020 × 21% = 1,184,404.

PKM on holidays will be:

2016: 3,109,362 × 23% = 715,153.

2026: 4,163,660 × 23% = 957,642.

2036: 5,155,862 × 23% = 1,185,848.

2040: 5,640,020 × 23% = 1,297,205.

1.12. PKM per Year

Considering the 2016 calendar there is 252 business days; 52 Saturdays; 52 Sundays and holidays nine. The total PKM per year will be:

2016: 252 × 3,109,362 + 52 × 1,212,651 + 52 × 652,966 + 9 × 715,153 = 887,007,658 (It was considered half of this value — 443,503,829 — because L4 starts operation on second half of 2016).

2026: 252 × 4,163,660 + 52 × 1,623,827 + 52 × 874,369 + 9 × 957,642 = 1,187,767,243.

2036: 252 × 5,155,862 + 52 × 2,010,786 + 52 × 1,082,731 + 9 × 1,185,848 = 1,470,812,762.

2040: 252 × 5,640,020 + 52 × 2,199,608 + 52 × 1,184,404 + 9 × 1,297,205 = 1,608,928,623.

Annual growth rate:
Between 2016 and 2026: $(1,187,767,243/887,007,658)^{1/10} - 1 = 2.96\%$.
Between 2026 and 2036: $(1,470,812,762/1,187,767,243)^{1/10} - 1 = 2.16\%$.
Between 2036 and 2046: $(1,608,928,623/1,470,812,762)^{1/4} - 1 = 2.27\%$.

Considering the annual growth rate, the PKM in each year is presented in Table S10.

Table S10. PKM per year.

Year	PKM
second half of 2016	443,503,829
2017	913,288,032
2018	940,347,045
2019	968,207,766
2020	996,893,947
2021	1,026,430,046
2022	1,056,841,245
2023	1,088,153,470
2024	1,120,393,418
2025	1,153,588,575
2026	1,187,767,243
2027	1,213,427,822
2028	1,239,642,773
2029	1,266,424,074
2030	1,293,783,959
2031	1,321,734,928
2032	1,350,289,751
2033	1,379,461,474
2034	1,409,263,424
2035	1,439,709,217
2036	1,470,812,762
2037	1,504,188,405
2038	1,538,321,407
2039	1,573,228,954
2040	1,608,928,623
TOTAL	**30,504,632,189**
Annual average	**1,245,087,028**

2. Credit (Energy and CO_2 Emissions Avoided by L4)

2.1. PKM Split between Buses and Automobiles. VKM and Quantity of Fuel

72% of the users were from buses (fueled by diesel) and 28% from automobiles [2].
The automobile fleet of the city has [3] (approximate, rounded numbers):
41.44% fueled only by gasoline,
6.00% fueled only by hydrous ethanol,
21.41% fueled by compressed natural gas (CNG),
31.55% flex-fuel (fueled by gasoline and ethanol in any proportion).
According to Equation (11), the percent of ethanol used by flex-fuel cars is:

$$\% \text{ ethanol} = -3.6945 \times (\text{ethanol price} \div \text{gasoline price}) + 3.0219 \quad \text{(s1)}$$

The relation of prices has remained around 70%–80%. In 2014 it was 78.33% [4].
% ethanol = −3.6945 × (78.33%) + 3.0219 = 12.81%.
In flex-fuel there is 12.81% × 31.55 = 4.04% ethanol use and (31.55 − 4.04) = 27.51% gasoline use.
Gasoline is used by 41.44 + 27.51 = 68.95% of autos fleet,

Hydrous ethanol is used by 6.00 + 4.04 = 9.64% of autos fleet,

CNG is used by 21.41% of autos fleet.

PKM is split to VKM-autos and VKM-buses. For autos VKM = PKM/1.4, since the assumption is 1.4 passengers per auto. For buses the assumption is 80 passengers during peak hours and 40 passengers during off-peak hours.

Peak hours correspond to 20.70% (morning) + 25.80% (evening) = 46.50% of PKM [1].

Off–peak hours correspond to 53.50% of PKM.

Efficiency considered: autos gasoline–10 km/L; autos ethanol–8.65 km/L; autos CNG–12 km/m^3 and diesel bus–2.30 km/L.

The blend fuel for gasoline cars is 73% gasoline and 27% anhydrous ethanol. The blend fuel for diesel buses is 93% diesel and 7% biodiesel.

The symbol used for liter is "L" to avoid confusion between the letter "l" and the number "1".

2.1.1. Buses

Applying Equation (5):

VKM Bus = ((72% × PKM × 46.5%)/80) + ((72% × PKM × 53.5%)/40) = ((72% × 30,504,632,189 × 46.5%)/80) + ((72% × 30,504,632,189 × 53.5%/40) = 421,421,494

The fuel quantity Q_f for VKM bus is (Equation (6)):

Diesel:

Q_f = (VKM Bus/2.3) × 93% = (421,421,494/2.3) × 93% = **170,400,865 L**

Biodiesel:

Q_f = (VKM Bus/2.3) × 7% = (421,421,494/2.3) × 7% = **12,825,872 L**

2.1.2. Auto Gasoline

Applying Equation (5):

VKM Auto gasoline = (28% × PKM × 68.95%)/1.4 = (28% × 30,504,632,189 × 68.95%)/1.4 = 4,206,588,779

The fuel quantity Q_f for VKM Auto gasoline is (Equation (6)):

Gasoline:

Q_f = (VKM Auto gasoline/10) × 73% = (4,206,588,779/10) × 73% = **307,080,981 L**

Anhydrous Ethanol:

Q_f = (VKM Auto gasoline/10) × 27% = 4,206,588,779/10) × 27% = **113,577,897 L**

2.1.3. Auto Ethanol

Applying Equation (5):

VKM Auto ethanol = (28% × PKM × 9.64%)/1.4 = (28% × 30,504,632,189 × 9.64%)/1.4 = 588,129,309

The fuel quantity Q_f for VKM Auto ethanol is (Equation (6)):

Hydrous Ethanol:

Q_f = VKM Auto ethanol/8.65 = 588,129,309/8.65 = **67,991,828 L**

2.1.4. Auto CNG

Applying Equation (5):

VKM Auto CNG = (28% × PKM × 21.41%)/1.4 = (28% × 30,504,632,189 × 21.41%)/1.4 = 1,306,208,350

The fuel quantity Q_f for VKM Auto CNG is (Equation (6)):

CNG:

Q_f = VKM Auto CNG/12 = 1,306,208,350/12 = **108,850,696 m^3**

2.2. Avoided Energy and CO_2 Emissions by L4

Energy density and CO_2 emissions factors used are presented in Table S11.

Table S11. Energy density and CO_2 emissions factors, including upstream energy and CO_2 emissions.

Fuel	Energy Density	CO_2 Emission Factor	Source
Gasoline	36.36 MJ/L	2.57 $kgCO_2$/L	Calculated from ANP [4], D'Agosto [5] and IPCC [6]
Diesel	40.82 MJ/L	2.95 $kgCO_2$/L	Calculated from ANP [4], D'Agosto [7] and IPCC [6]
CNG	39.82 MJ/m^3	2.16 $kgCO_2/m^3$	COPPETEC [8] and D'Agosto [5]
Biodiesel	43.07 MJ/L	0.40 $kgCO_2$/L	ANP [4] and D'Agosto [7]
Hydrous Ethanol	33.71 MJ/L	0.09 $kgCO_2$/L	ANP [4] and D'Agosto [5]
Anhydrous Ethanol	24.60 MJ/L	0.02 $kgCO_2$/L	ANP [4] and D'Agosto [5]

Note: WTW values for Gasoline, Diesel and CNG CO_2 emission factor and all energy density. WTT values for Biodiesel/Anhydrous Ethanol/Hydrous Ethanol CO_2 emission factor.

Calculation for Gasoline and Diesel (TTW):
According to ANP [4], Brazilian fuels have:

Net calorific value: diesel = 10,100 kcal/kg and gasoline = 10,400 kcal/kg.
Density: diesel = 0.84 kg/L and gasoline = 0.742 kg/L.

1 kcal = 0.004184 MJ.
For diesel: Energy density =10,100 × 0.004184 × 0.84 = 35.50 MJ/L.
For gasoline: Energy density =10,400 × 0.004184 × 0.742 = 32.29 MJ/L.
According to IPCC (50) CO_2 emissions, per natural unit, can be estimated by:

$$NCV \times EF \times F \times (44/12)$$

where: NCV = Net calorific value (in TJ/natural unit), EF = carbon emission factor (carbon content, in tC/TJ), EF for diesel = 20.20 tC/TJ; EF for gasoline = 18.9 tC/TJ, F = oxidation factor = 0.99, 44/12 = conversion factor from carbon to carbon dioxide (CO_2).

CO_2 Emission factor for diesel = (35.50/1000000) TJ/L × 20.2 tC/TJ × 0.99 × (44/12) = 0.00260 tCO_2/L = 2.60 $kgCO_2$/L.

CO_2 Emission factor for gasoline = (32.29/1000000) TJ/L × 18.9 tC/TJ × 0.99 × (44/12) = 0.00222 tCO_2/L = 2.22 $kgCO_2$/L.

Adding the upstream energy and emissions (WTW):
Energy density for diesel = 40.82 MJ/L
Energy density for gasoline = 36.36 MJ/L
CO_2 Emission factor for diesel = 2.95 $kgCO_2$/L.
CO_2 Emission factor for gasoline = 2.57 $kgCO_2$/L.

2.2.1. Avoided Energy

Energy, calculated by Equation (7), is:
$En = Q_f \times E_d$
Gasoline: En = 307,080,981 × 36.36 = 11,165,464,464 MJ = **11,165 TJ**
CNG: En = 108,850,696 × 39.82 = 4,334,434,709 MJ = 4**334 TJ**
Diesel: Em = 170,400,865 × 40.82 = 6,955,763,303 MJ = **6956 TJ**
Anhydrous Ethanol: En = 113,577,897 × 24.60 = 2,794,016,267 MJ = **2794 TJ**
Hydrous Ethanol: En = 67,991,828 × 33.71 = 2,292,004,508 MJ = 2**292 TJ**
Biodiesel: En = 12,825,872 × 43.07 = 552,410,288 MJ = **552 TJ**
Total Non-Renewable Energy = 11,165,464,464 + 4,334,434,709 + 6,955,763,303 = 22,455,662,476 MJ = **22,456 TJ**
Total Renewable Energy = 2,794,016,267 + 2,292,004,508 + 552,410,288 = 5,638,431,062 MJ = **5638 TJ**
Total Energy = 22,455,662,476 + 5,638,431,062 = 28,094,093,538 MJ = **28,094 TJ**

2.2.2. Avoided CO_2 Emissions

CO_2 emissions, calculated by Equation (8), have values:

$Em = Q_f \times E_f$

Gasoline: Em = 307,080,981 × 2.57/1000 = **789,198 t CO_2**

CNG: Em = 108,850,696 × 2.16/1000 = **235,118 t CO_2**

Diesel: Em = 170,400,865 × 2.95/1000 = **502,863 t CO_2**

Anhydrous Ethanol: Em = 113,577,897 × 0.02/1000 = **2272 t CO_2**

Hydrous Ethanol: Em = 67,991,828 × 0.09/1000 = **6119 t CO_2**

Biodiesel: Em = 12,825,872 × 0.40/1000 = **5130 t CO_2**

Total CO_2 emissions = 789,198 + 235,118 + 502,863 + 2272 + 6119 + 5130 = **1,540,519 t CO_2**

3. Debit (Energy Consumed and CO_2 Emissions Produced by L4)

Energy Consumed and CO_2 Emissions Produced by L4

There are 149,220 train departures for a distance of 12.339 km and 97,812 train departures for a distance of 5.215 km.

The train has six cars. Reference load = 1820 passengers per train (or 1820/6 passengers per car).

Energy Consumed by L4

Total car-km per year is given by Equation (2):

c = d × l × n = (149,220 × 12.339 + 97,812 × 5.215) × 6 = 14,107,891 [1].

Total PKM = 30,504,632,189. Total PKM per year = 30,504,632,189/24.5 = 1,245,087,028.

PKM per year for the Reference Load = 14,107,891 × (1820/6) = 4,279,393,603.

Load = 1,245,087,028/4,279,393,603 = 29.09%.

Energy consumed per car-km for this load (Equation (9)):

c = 2.97 + (1.83 × 29.09%)/118% = 3.42 kWh/car-km [1].

According to Equation (2) and considering T&D losses = 12% [9,10]): Total energy consumed by year = (14,107,891 × 3.42)/0.88 = 54,828,394 kWh.

Total energy in the period: second half of 2016–2040 = 24.5 × 54,828,394 = 1,343,295,663 kWh = 3.6 × 1,343,295,663 = 4,835,864,387 MJ = **4836 TJ**

Brazilian electric matrix: 74.60% Renewable and 25.40% Non–Renewable [11].

Renewable = 74.60% × 4,835,864,387 = 3,607,554,833 MJ = **3608 TJ**

Non–Renewable = 25.40% × 4,835,864,387 = 1,228,309,554 MJ = **1228 TJ**

CO_2 Emissions Produced by L4

Applying Equation (4) of the article:

Emissions produced in the period: second half of 2016–2040 = 1,343,295,663 kWh × 0.1355 kgCO_2/kWh = **182,017 t CO_2**

4. Net Avoided Energy and CO_2 Emissions (Credit—Debit)

Net Avoided Non-Renewable Energy = 22,455,662,476 − 1,228,309,554 = 21,227,352,922 MJ = **21,227 TJ**

Net Avoided Renewable Energy = 5,638,431,062 − 3,607,554,833 = 2,030,876,229 MJ = **2031 TJ**

Net Avoided Energy = 28,094,093,538 − 4,835,864,387 = 23,258,229,151 MJ = **23,258 TJ**

Net Avoided Emissions = 1,540,519 − 182,017 = 1,358,503 t CO_2

Net Avoided Non-Renewable Energy per year = 21,227,352,922/24.5 = 866,422,568 MJ = **866 TJ**

Net Avoided Renewable Energy per year = 2,030,876,229/24.5 = 82,892,907 MJ = **83 TJ**

Net Avoided Energy per year = 23,258,229,151/24.5 = 949,315,476 MJ = **949 TJ**

Net Avoided Emissions per year = 1,358,503/24.5 = 55,449 t CO_2

Net Avoided Non-Renewable Energy per PKM = 21,227,352,922/30,504,632,189 = 0.70 MJ

Net Avoided Renewable Energy per PKM = 2,030,876,229/30,504,632,189 = 0.07 MJ

Net Avoided Energy per PKM = 23,258,229,151/30,504,632,189 = **0.76 MJ**
Net Avoided Emissions per PKM = (1,358,888/30,504,632,189) × 1,000,000 = **44.53 g CO_2**

5. Scenarios

Scenario A: the PKM value will increase, making passenger load equal to 50%. In this case, "debit" and "credit" will be affected.

Debit:

The energy consumption per car-km for load = 50% can be determined by applying Equation (10):

c = 2.97 + (1.83 × l)/118% = 2.97 + (1.83 × 50%)/118% = 3.75 kWh/car-km

Energy = (14,107,891 × 24.5 × 3.75)/0.88 kWh = 1,471,114,464 kWh = 1,472,911,915 × 3.6 = 5,296,012,069 MJ

Renewable Energy = 74.60% × 5,296,012,069 = 3,950,825,004 MJ

Non-Renewable Energy = 5,296,012,069 − 3,950,825,004 = 1,345,187,066 MJ

CO_2 emissions = (1,471,114,464 × 0.1355)/1000 = 199,336 t CO_2

Credit:

PKM is proportional to passenger load. PKM for load = 50% is:

$PKM_{L=50\%} = PKM_{L=29.09\%}$×(0.5/0.2909) = 30,504,632,189 × (0.5/0.2909) = 52,422,571,492

Applying Equation (5):

VKM Bus = ((72% × PKM × 46.5%)/80) + ((72% × PKM × 53.5%)/40) = ((72% × 52,431,475,059 × 46.5%)/80) + ((72% × 52,431,475,059 × 53.5%)/40) = 724,217,825

The fuel quantity Q_f for VKM bus is (Equation (6)):

Diesel: Q_f = (VKM Bus/2.3) × 93% = (724,217,825/2.3) × 93% = 292,835,903 L

Biodiesel: Q_f = (VKM Bus/2.3) × 7% = (724,217,825/2.3) × 7% = 22,041,412 L

Applying Equation (5):

VKM Auto gasoline = (28% × PKM × 68.95%)/1.4 = 7,229,437,709

The fuel quantity Q_f for VKM Auto gasoline is (Equation (6)):

Gasoline: Q_f = (VKM Auto gasoline/10) × 73% = 527,722,300 L

Anhydrous Ethanol: Q_f = (VKM Auto gasoline/10) × 27% = 195,184,960 L

Applying Equation (5):

VKM Auto ethanol = (28% × PKM × 9.64%)/1.4 = 1,010,257,572

The fuel quantity Q_f for VKM Auto ethanol is (Equation (6)):

Ethanol: Q_f = VKM Auto Ethanol/8.65= 116,844,761 L

Applying Equation (5):

VKM Auto CNG = (28% × PKM × 9.64%)/1.4 = 2,244,819,018

The fuel quantity Q_f for VKM Auto CNG is (Equation (6)):

CNG: Q_f = VKM Auto CNG/12= 187,061,209 m^3

Energy, calculated by Equation (7), is:

$En = Q_f \times E_d$

Gasoline: En = 527,722,300× 36.36 = 19,187,982,844 MJ

CNG: En = 187,061,209 × 39.82 = 7,448,777,353 MJ

Diesel: En = 292,835,903× 40.82 = 11,953,561,569 MJ

Anhydrous Ethanol: En =195,184,960 × 24.60 = 4,801,550,027 MJ

Hydrous Ethanol: En = 116,844,761× 33.71 = 3,938,836,877 MJ

Biodiesel: En = 22,041,412 × 43.07 = 949,323,618 MJ

Total Non-Renewable Energy = 19,187,982,844 + 7,448,777,353 + 11,953,561,569 = 38,590,321,767 MJ

Total Renewable Energy = 4,801,550,027 + 3,938,836,877 + 949,323,618 = 9,689,710,521 MJ

Total Energy = 38,590,321,767 + 9,689,710,521 = 48,280,032,288 MJ

CO_2 emissions, calculated by Equation (8), is:
$Em = Q_f \times E_f$
Gasoline: Em = 527,722,300 × 2.57/1,000 = 1,356,246 t CO_2
CNG: Em = 187,061,209 × 2.16/1,000 = 404,052 t CO_2
Diesel: Em = 292,835,903 × 2.95/1,000 = 863,866 t CO_2
Anhydrous Ethanol: Em = 195,184,960 × 0.02/1,000 = 3904 t CO_2
Hydrous Ethanol: Em = 116,844,761× 0.09/1,000 = 10,516 t CO_2
Biodiesel: Em = 22,041,412 × 0.40/1,000 = 8817 t CO_2

Total CO_2 emissions = 1,356,246 + 404,052 + 863,866 + 3,904 + 10,516 + 8817 = 2,647,401 t CO_2

Net avoided Energy and CO_2 Emissions (Credit – Debit):
Net Avoided Non-Renewable Energy = 38,590,321,767 − 1,345,187,066 = 37,245,134,701 MJ
Net Avoided Renewable Energy = 9,689,710,521 − 3,950,825,004 = 5,738,885,518 MJ
Net Avoided Energy = 48,280,032,288 − 5,296,012,069 = 42,984,020,219 MJ
Net Avoided Emissions = 2,647,401 − 199,336 = 2,448,065 t CO_2

Net Avoided Non-Renewable Energy per year = 37,245,134,701/24.5 = 1,520,209,580 MJ = **1520 TJ**
Net Avoided Renewable Energy per year = 5,738,885,518/24.5 = 234,240,225 MJ = **234 TJ**
Net Avoided Energy per year = 42,984,020,219/24.5 = 1,754,449,805 MJ = **1754 TJ**
Net Avoided Emissions per year = 2,448,065/24.5 = 99,921 t CO2
Sensitivity analysis:

Figure S1 and Table S12 shows the results for avoided and produced emissions, for different loads.

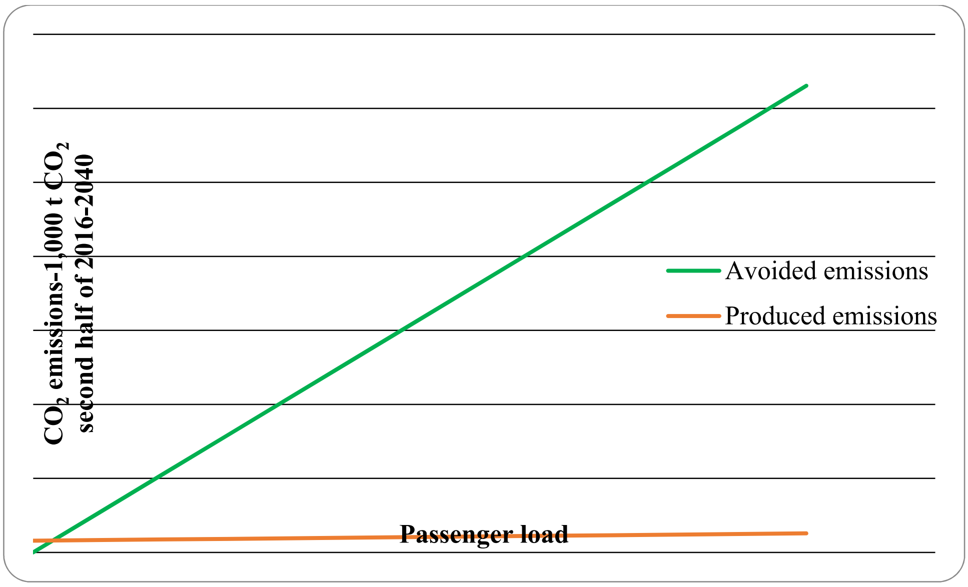

Figure S1. Sensitivity analysis of L4 transport performance.

Table S12. Avoided and produced emissions

Load	Avoided Emissions (1000 t CO_2)	Produced Emissions (1000 t CO_2)
0	0	158
10%	525	166
20%	1050	175
30%	1574	183
40%	2099	191
50%	2624	199
60%	3149	208
70%	3674	216
80%	4199	224
90%	4723	232
100%	5248	241
110%	5773	249
120%	6305	257

Scenario B: train departures decreases 30%, increasing passenger load. PKM does not change, so "Credit" will not be affected.

Debit:
Car-km also decreases 30%: car-km = 0.7 × 14,107,891 = 9,875,524 per year.
PKM remains the same: PKM = 1,245,087,028
PKM for the reference load is: PKM_{RL} = 9,875,524 × (1820/6) = 2,995,575,522
Load: 1,245,087,028/2,995,575,522 = 41.56%
Energy consumed per car-km for this load (Equation (10)):
c = 2.97 + (1.83 × 41.56%)/118% = 3.61 kWh/car-km [1].
Energy consumed: 9,875,524 × 3.61 × 24.5 = 992,546,243 kWh = 3.6 × 992,546,243 = 3,573,166,474 MJ
Energy Renewable: 74.60% × 3,573,166,474 = 2,665,582,190 MJ
Energy Non-Renewable: 25.40% × 3,573,166,474 = 907,584,284 MJ
CO_2 Emissions: 0.1355 × 992,546,243/1000 = 134,490 t CO_2

Credit:
As "Credit" is not affected is the same of the sudy:
Total Non-Renewable Energy = 22,455,662,476 MJ
Total Renewable Energy = 5,638,431,062 MJ
Total Energy = 28,094,093,538 MJ
Total CO_2 emissions = 1,540,519 t CO_2
Net Avoided per year:
Total Non-Renewable Energy = (22,455,662,476 − 907,584,284)/24.5 = 879,513,396 MJ = **880 TJ**
Total Renewable Energy = (5,638,431,062 − 2,665,582,190)/24.5 = 121,340,770 MJ = **121 TJ**
Total Energy = (28,094,093,538 − 3,573,166,474)/24.5 = 1,000,854,166 MJ = **1001 TJ**
Total CO_2 emissions = (1,540,519 − 134,490)/24.5 = **57,389 t CO_2**

Scenario C: the electricity mix has higher carbon intensity. The average European emission factor of 2015 (0.35047 kgCO_2/kWh) was used [5].
The only change will be in CO_2 emissions (debit).

Debit:
1,343,295,663 kWh × 0,35047 kgCO_2/kWh = 470,785 t CO_2

Credit:
As "Credit" is not affected, is the same of the sudy:
Total Non-Renewable Energy = 22,455,662,476 MJ
Total Renewable Energy = 5,638,431,062 MJ
Total Energy = 28,094,093,538 MJ
Total CO_2 emissions = 1,540,519 t CO_2

Net Avoided per year:
Total Non-Renewable Energy = (22,455,662,476 − 3,177,015,864)/24.5 = 786,883,535 MJ = **787 TJ**
Total Renewable Energy = (5,638,431,062 − 1,658,848,524)/24.5 = 162,431,940 MJ = **162 TJ**
Total Energy = (28,094,093,538 − 4,835,864,387)/24.5 = 949,315,476 MJ = **949 TJ**
Total CO_2 emissions = (1,540,519 − 470,785)/24.5 = **43,663 t CO_2**

Scenario D: there is no consumption of alternative fuels. All cars use gasoline and all buses use diesel.

Debit:
Debit does not change, is the same of the study:
Energy consumed = 4,835,864,387 MJ.
Renewable = 3,607,554,833 MJ.
Non–Renewable = 1,228,309,554 MJ.
CO_2 Emissions = 182,017 t CO_2.

Credit:
Applying Equation (5):
VKM Bus = ((72% × PKM × 46.5%)/80) + ((72% × PKM × 53.5%)/40) = ((72% × 30,504,632,189) × 46.5%)/80) + ((72% × 30,504,632,189) × 53.5%)/40) = 421,421,494
The fuel quantity Q_f for VKM bus is (Equation (6)):
Diesel: Q_f = (VKM Bus/2.3) = 421,421,494/2.3 = 183,226,736 L

Applying Equation (5):
VKM Auto gasoline = (28% × PKM)/1.4 = (28% × 30,504,632,189/1.4 = 6,100,926,438
The fuel quantity Q_f for VKM Auto gasoline is (Equation (6)):
Gasoline: Q_f = (VKM Auto gasoline/10) = 6,100,926,438/10 = 610,092,644 L

Energy, calculated by Equation (7), is:
$En = Q_f \times E_d$
Gasoline: En = 610,092,644 × 36.36 = 22,182,968,528 MJ
Diesel: Em = 183,226,736 × 40.82= 7,479,315,379 MJ
Total Non-Renewable Energy = 22,182,968,528 + 7,479,315,379 = 29,662,283,907 MJ
Total Renewable Energy = 0 MJ
Total Energy = 29,662,283,907 + 0 = 29,662,283,907 MJ

CO_2 emissions, calculated by Equation (8), is:
$Em = Q_f \times E_f$
Gasoline: Em = 610,092,644 × 2.57/1,000 = 1,567,938 t CO_2
Diesel: Em = 183,226,736 × 2.95/1,000 = 540,519 t CO_2
Total CO_2 emissions = 1,567,938 + 540,519 = 2,108,457 t CO_2
Net Avoided per year:
Total Non-Renewable Energy = (29,662,283,907 − 1,228,309,554)/24.5 = 1,160,570,382 MJ = **1161 TJ**
Total Renewable Energy = (0 − 3,607,554,833)/24.5 = −147,247,136 MJ = −**147 TJ**
Total Energy = (29,662,283,907 − 4,835,864,387)/24.5 = 1,013,323,246 MJ = **1013 TJ**
Total CO_2 emissions = (2,108,457 − 182,017)/24.5 = **78,630 t CO_2**

Scenario E: the passenger load of cars increases to three passengers.

Debit:
Debit is not affected:
Energy consumed = 4,835,864,387 MJ
Renewable = 3,607,554,833 MJ
Non–Renewable = 1,228,309,554 MJ
CO_2 Emissions = 182,017 t CO_2.

Credit:
Applying Equation (5):
VKM Bus = ((72% × PKM × 46.5%)/80) + ((72% × PKM × 53.5%)/40) = ((72% × 30,504,632,189) × 46.5%)/80) + ((72% × 30,504,632,189) × 53.5%)/40) = 421,421,494
The fuel quantity Q_f for VKM bus is (Equation (6)):
Diesel: Q_f = (VKM Bus/2.3) × 93% = (421,421,494/2.3) × 93% = 170,400,865 L
Biodiesel: Q_f = (VKM Bus/2.3) × 7% = (421,421,494/2.3) × 7% = 12,825,872 L

Applying Equation (5):
VKM Auto gasoline = (28% × PKM × 68.95%)/3 = (28% × 30,504,632,189 × 68.95%)/3 = 1,963,074,763
The fuel quantity Q_f for VKM Auto gasoline is (Equation (6)):
Gasoline:
Q_f = (VKM Auto gasoline/10) × 73% = 1,963,074,763/10) × 73% = 143,304,458 L
Anhydrous Ethanol:
Q_f = (VKM Auto gasoline/10) × 27% = 1,963,074,763/10) × 27% = 53,003,019 L

Applying Equation (5):
VKM Auto ethanol = (28% × PKM × 9.64%)/3 = (28% × 30,504,632,189 × 9.64%)/3 =274,460,344
The fuel quantity Q_f for VKM Auto ethanol is (Equation (6)):
Hydrous Ethanol:
Q_f = VKM Auto ethanol/8.65 = 31,729,520 L

Applying Equation (5):
VKM Auto CNG = (28% × PKM × 21.41%)/3 = (28% × 30,504,632,189 × 21.41%)/3 = 609,563,897
The fuel quantity Q_f for VKM Auto CNG is (Equation (6)):
CNG:
Q_f = VKM Auto CNG/12 = 609,563,897/12 = 50,796,991 m^3

Energy, calculated by Equation (7), is:
En = Q_f × E_d
Gasoline --------- En = 143,304,458 × 36.36 = 5,210,550,083 MJ
CNG ----------- Em = 50,796,991× 39.82 = 2,022,736,198 MJ
Diesel ---------- Em = 170,400,865 × 40.82 = 6,955,763,303 MJ
Anhydrous Ethanol -------- En = 53,003,019 × 24.60 = 1,303,874,258 MJ
Hydrous Ethanol --------- En = 31,729,520 × 33.71 = 1,069,602,104 MJ
Biodiesel ---------- En = 12,825,872 × 43.07 = 552,410,288 MJ
Total Non-Renewable Energy = 5,210,550,083 + 2,022,736,198 + 6,955,763,303 = 14,189,049,584 MJ
Total Renewable Energy = 1,303,874,258 + 1,069,602,104 + 552,410,288 = 2,925,886,649 MJ
Total Energy = 14,189,049,584 + 2,925,886,649 = 17,114,936,233 MJ

CO_2 emissions, calculated by Equation (8), is:
Em = Q_f × E_f
Gasoline --------- Em = 143,304,458 × 2.57/1000 = 368,292 t CO_2
CNG ----------- Em = 50,796,991 × 2.16/1000 = 109,722 t CO_2
Diesel ---------- Em = 170,400,865 × 2.95/1000 = 502,683 t CO_2
Anhydrous Ethanol: Em = 53,003,019 × 0.02/1000 = 1060 t CO_2
Hydrous Ethanol: Em = 31,729,520 × 0.09/1000 = 2856 t CO_2

Biodiesel: Em = 12,825,872 × 0.40/1,000 = 5130 t CO_2
Total CO_2 emissions = 368,292 + 109,722 + 502,683 + 1060 + 2856 + 5130 = 989,743 t CO_2
Net Avoided per year:
Total Non-Renewable Energy = (14,189,049,584 − 1,228,309,554)/24.5 = 529,009,797 MJ = **529 TJ**
Total Renewable Energy = (2,925,886,649 − 3,607,554,833)/24.5 = −27,823,191 MJ = **−28 TJ**
Total Energy = (17,114,936,233 − 4,835,864,387)/24.5 = 501,186,606 MJ = **501 TJ**
Total CO_2 emissions = (989,743 − 182,017)/24.5 = **32,968 t CO_2**

Scenario F: the proportion of cars and buses changes from 28% to 42% for cars (growth of 50%) and from 72% to 58% for buses.

Debit:
Debit is not affected:
Energy consumed = 4,835,864,387 MJ
Renewable = 3,607,554,833 MJ
Non–Renewable = 1,228,309,554 MJ
CO_2 Emissions = 182,017 t CO_2.

Credit:
Applying Equation (5):
VKM Bus = ((58% × PKM × 46.5%)/80) + ((58% × PKM × 53.5%)/40) = ((58% × 30,504,632,189) × 46.5%)/80) + ((58% × 30,504,632,189) × 53.5%)/40) = 339,478,425
The fuel quantity Q_f for VKM bus is (Equation (6)):
Diesel: Q_f = (VKM Bus/2.3) × 93% = (339,478,425/2.3) × 93% = 137,267,363 L
Biodiesel: Q_f = (VKM Bus/2.3) × 7% = (339,478,425/2.3) × 7% = 10,331,952 L

Applying Equation (5):
VKM Auto gasoline = (42% × PKM × 68.95%)/1.4 = (42% × 30,504,632,189 × 68.95%)/1.4 = 6,309,883,168
The fuel quantity Q_f for VKM Auto gasoline is (Equation (6)):
Gasoline: Q_f = (VKM Auto gasoline/10) × 73% = (6,309,883,168/10) × 73% = 460,621,471 L
Anhydrous Ethanol: Q_f = (VKM Auto gasoline/10) × 27% = (6,309,883,168/10) × 27% = 170,366,846 L

Applying Equation (5):
VKM Auto ethanol = (42% × PKM × 9.64%)/1.4 = (42% × 30,504,632,189 × 9.64%)/1.4 = 882,193,963
The fuel quantity Q_f for VKM Auto ethanol is (Equation (6)):
Ethanol: Q_f = VKM Auto ethanol/8.65 = 882,193,963/8.65 = 101,987,741 L

Applying Equation (5):
VKM Auto CNG = (42% × PKM × 9.64%)/1.4 = (42% × 30,504,632,189 × 9.64%)/1.4 = 1,959,312,526
The fuel quantity Q_f for VKM Auto CNG is (Equation (6)):
CNG: Q_f = VKM Auto CNG/12 = 1,959,312,526/12 = 163,276,044 m^3

Energy, calculated by Equation (7), is:
En = Q_f × E_d
Gasoline: En = 460,621,471× 36.36 = 16,748,196,696 MJ
CNG: Em = 163,276,044 × 39.82 = 6,501,652,064 MJ
Diesel: Em = 137,267,363× 40.82 = 5,603,253,772 MJ
Anhydrous Ethanol: En = 170,366,846 × 24.60 = 4,191,024,400 MJ
Hydrous Ethanol: En = 101,987,741× 33.71 = 3,438,006,762 MJ
Biodiesel: En = 10,331,952 × 43.07 = 444,997,176 MJ
Total Non-Renewable Energy = 16,748,196,696 + 6,501,652,064 + 5,603,253,772 = 28,853,102,532 MJ
Total Renewable Energy = 4,191,024,400 + 3,438,006,762 + 444,997,176 = 8,074,028,338 MJ
Total Energy = 28,853,102,532 + 8,074,028,338 = 36,927,130,870 MJ

CO_2 emissions, calculated by Equation (8), is:

$Em = Q_f \times E_f$

Gasoline: Em = 460,621,471 × 2.57/1000 = 1,183,797 t CO_2

CNG: Em = 163,276,044 × 2.16/1000 = 352,676 t CO_2

Diesel: Em = 137,267,363 × 2.95/1000 = 404,939 t CO_2

Anhydrous Ethanol: Em = 170,366,846 × 0.02/1000 = 3407 t CO_2

Hydrous Ethanol: Em = 101,987,741 × 0.09 = 9179 t CO_2

Biodiesel: Em = 10,331,952 × 0.40 = 4133 t CO_2

Total CO_2 emissions = 1,183,797 + 352,676 + 404,939 + 3407+ 9179 + 4133 = 1,958,131 t CO_2

Net Avoided per year:

Total Non-Renewable Energy = (28,853,102,532 − 1,228,309,554)/24.5 = **=** 1,127,542,570 = **1128 TJ**

Total Renewable Energy = (8,074,028,338 − 3,607,554,833)/24.5 = 182,305,041 = **182 TJ**

Total Energy = (36,927,130,870 − 4,835,864,387)/24.5 = 1,309,847,612 = **1310 TJ**

Total CO_2 emissions = (1,958,131 − 182,017)/24.5 = **72,494 t CO_2**

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