Appendix A Mathematical notations

TableA1 List of mathematical notations

Notation	Definition	First appeared section and equation
x	The input variable	Section3.1.1 Equation (1)
y	The desired output variable	Section3.1.1 Equation (1)
b	The non-desired output variable	Section3.1.1 Equation (1)
$P(x)$	The set of production possibilities	Section3.1.1 Equation (1)
$g = (g_y, g_b)$	The directional vector of directional distance functions	Section3.1.1 Equation (2)
$g_y(g_b)$	The direction and size of the (non-)desired output change	Section3.1.1 Equation (2)
$\overrightarrow{D_0}$	The directional distance function	Section3.1.1 Equation (2)
β	The coefficient of g_b in $\overrightarrow{D_0}$	Section3.1.1 Equation (2)
R	The profit function for this production	Section3.1.2 Equation (3)
l	The coefficient of x in R	Section3.1.2 Equation (3)
p	The coefficient of y in R	Section3.1.2 Equation (3)
q	The coefficient of y in R, which is also the marginal abatement cost of the undesired output	Section3.1.2 Equation (3)
$\alpha, \gamma, \mu, \eta, \psi$	The coefficients of the variables in $\overrightarrow{D_0}$ when $g = (g_y, g_b)$	Section3.1.3 Equation (11)
R	The carbon emissions of the vehicles produced by the enterprise during the operation phase	Section3.2.2 Equation (14)
P	The vehicle production	Section3.2.2 Equation (14)
FC_a	The fuel consumption of vehicles	Section3.2.2 Equation (14)
EF	The emission factor	Section3.2.2 Equation (14)
L	The average annual mileage	Section3.2.2 Equation (14)
$MAC(A_{ni})$	The marginal abatement cost of enterprise i when its emission reduction is A_{ni}	Section3.2.3 Equation (15)
C_{ni}	The initial carbon emission	Section3.2.3 Equation (15)

α_i	The constant parameter to be estimated	Section3.2.3 Equation (15)
β_i	The parameter determines the slope of the MAC curve	Section3.2.3 Equation (15)
$c \in [\underline{c}, \overline{c}]$	The production cost of the seller to provide Q units of carbon quotas	Section4.1 Equation (16)
p_b	The buyer's proposal price for carbon quotas	Section4.1 Equation (16)
p_s	The seller's proposal price for carbon quotas	Section4.1 Equation (16)
k	This parameter reflects the extent to which the government cares for (supports) both buyers and sellers.	Section4.1 Equation (16)
U_s	The seller's utility function	Section4.1 Equation (16)
$v \in [\underline{v}, \overline{v}]$	The value of Q units of carbon quotas to the buyer	Section4.1 Equation (17)
U_b	The buyer's utility function	Section4.1 Equation (17)
$E[p_b(v) \mid p_b(v) \geq p_s]$	The buyer's expected buyer's bid	Section4.1 Equation (18)
$E[p_s(c) \mid p_b \geq p_s(c)]$	The seller's asking price expected by the buyer	Section4.1 Equation (19)
a_s	The constant term in the seller's linear equilibrium bid	Section4.1 Equation (20)
β_s	The coefficient in the seller's linear equilibrium bid	Section4.1 Equation (20)
a_b	The constant term in the buyer's linear equilibrium bid	Section4.1 Equation (20)
β_b	The coefficient in the buyer's linear equilibrium bid	Section4.1 Equation (20)
$p_s^*(c)$	The seller's proposal price for a buyer-seller price game to reach a Nash equilibrium	Section4.1 Equation (29)
$p_b^*(v)$	The buyer's proposal price for a buyer-seller price game to reach a Nash equilibrium	Section4.1 Equation (29)
p^E	The transaction price based on quotations from both parties	Section4.1 Equation (30)
o_{mean}	The current official government guideline price	Section4.1 Equation (31)
o_{min}	The minimum price allowed by the government for carbon trading, set at 50% of the official government guideline price	Section4.1 Equation (31)
o_{max}	The maximum price allowed by the government for carbon trading, set at 150% of the official government guideline	Section4.1 Equation (31)

	price	

Appendix B Data on input-output indicators for automotive companies

TableB1 Energy consumption of cars in the complete vehicle manufacturing process

Type of Vehicles	New Energy Vehicle	Conventional Fuel Vehicle
Energy Consumption (t Standard Coal/Unit)	0.5	0.3942

TableB2 Data on input-output indicators for representative automotive companies

Enterprise	Year	Input indicators			Desired output	Undesired output
		Energy consumption (10kt Standard coal)	Employees in service (10k)	R&D investment (100M Yuan)	Operating profit (100M Yuan)	CO2 emission (10kt CO_2)
SAIC	2020	231.95	20.48	149.67	356.07	1098.61
	2019	276.42	21.64	147.68	403.45	1393.67
	2018	319.52	21.75	159.21	536.74	1621.05
	2017	327.95	18.07	110.62	541.10	1697.88
	2016	398.79	17.14	94.09	485.83	2128.08
GAC	2020	100.40	9.37	51.25	56.38	507.84
	2019	100.55	9.39	50.41	56.82	508.01
	2018	109.03	9.49	48.89	116.45	574.23
	2017	100.59	8.43	30.03	118.07	540.63
	2016	83.32	7.57	23.89	68.32	449.04
BAIC-Bluepark	2020	0.52	0.53	15.82	-65.59	0.73
	2019	1.75	0.57	15.45	-1.65	2.44
	2018	4.34	0.40	11.28	1.45	6.06
	2017	3.16	0.30	7.88	0.26	4.40
DFMC	2020	0.01	0.50	3.87	6.00	59.11
	2019	0.54	0.70	4.84	4.04	2.53
	2018	0.89	0.69	4.91	5.08	4.42
	2017	1.26	0.66	6.11	-0.89	6.96
	2016	38.30	0.68	6.50	0.85	328.34
Chang'an	2020	48.60	4.03	41.42	26.24	236.90
	2019	42.16	3.68	44.78	-21.07	200.73
	2018	42.55	3.60	38.23	-2.01	208.00
	2017	54.26	3.91	36.31	71.52	270.64
	2016	506.96	4.12	32.03	94.58	2614.23
GWM	2020	44.19	6.32	51.50	57.52	211.46
	2019	45.33	5.98	42.48	47.77	219.22
	2018	43.76	6.35	39.59	62.32	230.15

	2017	45.76	6.85	33.65	58.54	256.18
	2016	75.62	7.16	31.80	122.61	436.78
JMCG	2020	2.31	1.34	16.65	6.13	7.84
	2019	2.57	1.48	19.37	1.11	8.52
	2018	0.69	1.65	17.35	1.98	2.56
	2017	1.88	1.73	20.55	1.29	6.92
	2016	60.81	1.69	19.37	9.54	225.45
JAC	2020	7.32	2.47	18.10	1.26	25.30
	2019	7.51	2.45	16.04	2.31	20.34
	2018	9.33	2.66	21.31	-15.19	25.89
	2017	10.59	3.05	19.97	1.99	39.20
	2016	89.57	2.87	21.58	-26.48	400.63
Haima	2020	0.71	0.31	2.35	-11.85	3.05
	2019	1.43	0.37	6.79	0.88	4.83
	2018	2.98	0.63	9.48	-23.3461	11.41
	2017	6.69	0.82	6.64	-14.58	32.84
	2016	11.00	0.96	7.20	-0.3	57.84
BYD	2020	18.88	22.43	85.56	70.85773	76.94
	2019	20.24	22.92	84.21	23.12288	56.04
	2018	20.59	22.02	85.36	42.4176	47.93
	2017	15.03	20.09	62.66	54.10551	39.76
	2016	20.21	19.38	45.22	58.49534	69.67

TableB3 Statistical description of input-output indicators

Indicators	Mean value	Maximum value	Minimum value	Standard deviation
Energy consumption (10kt Standard coal)	68.55	506.96	0.01	111.85
Employees in service (10k)	6.77	22.92	0.30	7.51
Number of employees in service (10k)	39.18	159.21	2.35	38.47
Operating profit (100M Yuan)	69.20	541.10	-65.59	140.96
CO2 emission (10kt CO_2)	490.35	3720.45	0.07	824.95

Appendix C Data related to the mid-long term carbon trading SDM study

TableC1 R&D investment by representative vehicle companies around the world

Enterprise	Sales(10k Units)	Operating income (Billion RMB Yuan)	R&D Investment (Billion RMB Yuan)	Share of R&D investment	
Tesla	93.60	376.12	18.11	5.00%	https://data.eastmoney.com/notices/stock/TSLA.html
NIO	9.1429	36.10	4.59	12.70%	https://data.eastmoney.com/notices/stock/NIO.html
Xiaopeng	9.8155	20.99	4.11	19.60%	https://data.eastmoney.com/notices/stock/XPEV.html
LiXiang	9.0491	27.01	3.29	12.00%	https://data.eastmoney.com/notices/stock/LI.html
GWM	128.00	136.40	9.07	6.65%	https://data.eastmoney.com/notices/stock/601633.html
Geely	132.80	101.60	5.50	5.40%	https://data.eastmoney.com/notices/stock/00175.html
BYD	74.01	216.14	10.63	4.91%	https://data.eastmoney.com/notices/stock/002594.html
VW	888.20	1839.47	114.69	7.60%	https://annualreport2022.volkswagenag.com/
Ford	394.20	952.74	53.11	5.57%	https://sharehold

					er.ford.com/Investors/financials/default.aspx

TableC2 Net profit margins of the top five car companies by market capitalization in 2021

Enterprises	Net profit margins
BYD	2.27%
GWM	4.93%
SAIC	3.15%
GAC	9.69%
Chang'an	3.37%

Appendix D Input parameters for system dynamics model

TabelD1 Initial input data for whole life cost

Type	Attribute	Unit	Shape		
			S[a]	M[a]	L[a]
CV	Initial fuel consumption	L/100 km	6	8	10
	Initial production capacity	vehicle/year x10^4	500	1500	500
	Unit capacity investment cost	CNY/vehicle x10^4	1	1.2	1.5
	Base fixed cost	CNY/vehicle x10^4	1	1.2	1.5
	Glider cost	CNY/vehicle x10^4	3	6	9
	Initial cost of Internal combustion engine (CV)	CNY/vehicle x10^4	2	3	4
	Fractional reduction of Internal combustion engine (CV)	—	0.01	0.01	0.01
	Initial Maturity of Internal combustion engine (CV)	—	0.70	0.70	0.70
	Maintenance cost	CNY/year	1500	3000	4500
	Insurance premium	CNY/year	3000	5000	6000
BEV	Initial electricity consumption	kWh/100 km	15	18	21
	Initial production capacity	vehicle/year x10^4	0	0	0
	Unit capacity investment cost	CNY/vehicle x10^4	1.2	1.5	1.8
	Base fixed cost	CNY/vehicle x10^4	1.2	1.5	1.8
	Glider cost	CNY/vehicle x10^4	3	6	9
	Initial cost of BEV battery	CNY/vehicle x10^4	10	20	30
	Fractional reduction of BEV battery	—	0.1	0.1	0.1
	Initial Maturity of BEV battery	—	0.30	0.30	0.30
	Maintenance cost	CNY/year	450	900	1350
	Insurance premium	CNY/year	4500	6500	9000
PHEV	Initial electricity consumption	kWh/100 km	—	18	21
	Initial fuel consumption	vehicle/year x10^4	—	2	4
	Initial production capacity	vehicle/year x10^4	—	0	0
	Unit capacity investment cost	CNY/vehicle x10^4	—	1.8	2
	Base fixed cost	CNY/vehicle x10^4	—	2	2
	Glider cost	CNY/vehicle x10^4	—	6	9
	Initial cost of Internal combustion engine (PHEV)	CNY/vehicle x10^4	—	2	3
	Initial cost of PHEV battery	CNY/vehicle x10^4	—	12	18

	Initial Maturity of PHEV battery	—	—	0.3	0.3
	Maintenance cost	CNY/year	—	2000	3000
	Insurance premium	CNY/year	—	5500	7500
CV/ BEV/ PHEV	Cost of Vehicle license plate	CNY	70000 (megalopolis) or 0 (other cities and rural areas)		
	Annual travel distance	km/year	15000		
	Purchase tax	—	10%		
	Average years kept	Year	15		
	Oil price	CNY/L	6.5		
	Electricity	CNY/kWh	0.6 (day) or 0.3 (night)		
	Road tolls	CNY/year	1400		
	V&V tax	CNY/year	950		
	Cost of Driving restriction	CNY/year	1000 (megalopolis) or 0 (other cities and rural areas)		
	Park charges	CNY/year	4800 (megalopolis) or 2400 (other cities) or 0 (rural area)		
	Cost of congestion	CNY/year	1500 (megalopolis) or 750 (other cities) or 0 (rural area)		

TabelD2 Initial input data for vehicle attributes

Attribute	Consumer sensitivity to attributes	Initial Value		
		CV	BEV	PHEV
Environmental Friendliness	0.67	0.73	0.96	0.7
Power	0.94	0.85	0.72	0.77
Reliability	0.94	0.95	0.83	0.80
Safety	0.91	0.95	0.60	0.85
Convenience	0.80	1	0.05	0.60
Popularity	0.70	—	—	—
Choice Space	0.68	—	—	—

TabelD3 Calibration parameters of the model

Parameter	Value
Sensitivity of convenience to effective infrastructure	1.2
Base prevalence for popularity	0.5

Sensitivity of popularity to prevalence	**1**
Market share for base choice availability	**0.1**
Sensitivity of availability to sales	**0.6**
Base utilization	**0.7**
Reference utilization discrepancy	**0.1**
Sensitivity of adjustment to utilization	**0.5**
Sensitivity of capacity adjustment to policy penalty	**1.5**
Sensitivity of price adjustment to utilization	**0.8**
Sensitivity of price adjustment to penalty	**0.7**
Sensitivity of R&D adjustment to penalty	**1.5**