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EMISIJA UGLJIČNOG DIOKSIDA PRI IZGARANJU MOTORNIH GORIVA

Sažetak

Prikazan je utjecaj motornih goriva i pogonskih motora osobnih vozila na emisiju ugljičnog dioksida CO_2. Definirani su maseni i volumetrijski indeks i faktor emisije fosilnih goriva i izračunate njihove vrijednosti za najvažnija fosilna motorna goriva. Predstavljen je trend smanjenja specifične emisije CO_2 [g CO_2/km] osobnih vozila za razdoblje 1995.–2020. koji su predložili proizvođači vozila.

Analizirani su procesi pretvaranja primarne energije goriva u pogonskim motorima vozila i njihov utjecaj na stupanj iskorištenja motora i emisiju CO_2 vozila. Na osnovi rezultata statističke obrade podataka o deklariranom – tvorničkom i cestovnom specifičnom utrošku goriva [l/100 km] triju grupa vozila s benzinskim motorom, grupiranih po stapajnom obujmu motora, zbirno je ocijenjen utjecaj emisije CO_2 na okoliš.

1. Uvod

Od ukupne emisije CO_2 u okoliš svega 3% prouzroči čovjek svojim aktivnostima i od toga se 12% odnosi na antropogenu emisiju CO_2 prijevoznih vozila, koja koriste motorna goriva. Raspodjela antropogene emisije po pojedinim vidovima prijevoza, prikazana je u tablici 1. Istraživanja pokazuju pojačan porast ove emisije, pogotovo u posljednih 15 godina i to osobito u zemljama u brzom gospodarskom razvoju (u Europi, Indiji, Kini,...), pojačanim prijevozom ljudi i robe, sve većom gustoćom prometa u urbanim sredinama, mobilnošću pučanstva i drugih razloga. To sve uzrokuje povećanje godišnje potrošnje goriva, a time i emisije CO_2.

S druge strane, cestovni promet ima danas središnji utjecaj u zadovoljavanju potreba za mobilnošću suvremenog društva zbog svojih sustavnih osobina, kao što su velika fleksibilnost te trajna pouzdanost. Tehnička inovacija je osnovni koncept ekološke politike, kojeg prihvaća motorna industrija s ciljem smanjivanja sveukupnih ekonomskih troškova zaštite okoliša.

Tablica 1: Raspored antropogenih emisija (po [1])
Table 1: Anthropogenic emissions (according to [1])

Potrošači energije goriva / Fuel energy consumers	% udjela / Portion [%]
Termoenergane / Thermo power plants	25
Brodovi / Ships	1,5
Zrakoplovstvo / Airplanes	3
Industrija / Industry	19
Izgaranje biomase / Biomass burning	15
Osobna vozila / Automotive vehicles (cars)	5,5
Gospodarska vozila / Trucks, buses	6,0
Domaćinstva / Domestic heating	23
Ostali vidovi prijevoza / Other means of transportation	2

Poznato je, da su npr. troškovi tehničkih zahvata, smanjivanje jedne suvišne tone emisije CO_2, koju motorizirano vozilo emitira u okoliš, tri do osam puta veći od troškova zahvata s istim ciljem u drugim sektorima industrije, energetike i domaćinstava [1]. Emisiju CO_2 motoriziranih cestovnih vozila načelno je moguće smanjiti:

- optimiranjem procesa izgaranja, efektivnih radnih parametara motora, uključujući uređaj za naknadni tretman ispušnih plinova, radne parametre vozila, sve s ciljem maksimiranja energetske ekonomičnosti i smanjenja specifične potrošnje goriva (g/kWh, l/km),
- prelaskom na goriva s manjim sadržajem ugljika (plinovita goriva, alkoholi), bio-goriva, smjese bio- i fosilnih goriva, te goriva bez sadržaja ugljika, npr. H_2.

U realizaciji ovih zahtjeva značajnu, dapače, stratešku ulogu imaju:

- naftna industrija, s razvojem i proizvodnjom kvalitetnih motornih goriva, mazivih ulja, izgradnjom suvremenih rafinerija i infrastrukture, ponudom raznih vrsta goriva, njihovih smjesa i emulzija, te njihovu jednostavnu i brzu uporabu (u dovoljnoj količini),
- motorna industrija s inovativnim razvojem i kvalitetnom proizvodnjom motora i vozila,
- društvena zajednica s ekološki povoljnom zakonskom regulativom, ekonomskom, financijskom i poreznom politikom.

2. Parametri za ocjenu emisije CO_2 prijevoznih vozila

U ispušnim plinovima pri izgaranju fosilnih goriva u motorima s unutarnjim izgaranjem (MUIZ) CO_2 je pored vodene pare prisutan u najvećem postotku. Tako za potpuno izgaranje monokomponentnih C_nH_m goriva, pri stehiometrijskim uvjetima vrijedi:

$$C_nH_m + k \cdot O_2 + 3{,}76 \cdot k \cdot N_2 \rightarrow n \cdot CO_2 + \frac{m}{2} \cdot H_2O + 3{,}76 \cdot k \cdot N_2 \qquad (1)$$

gdje je

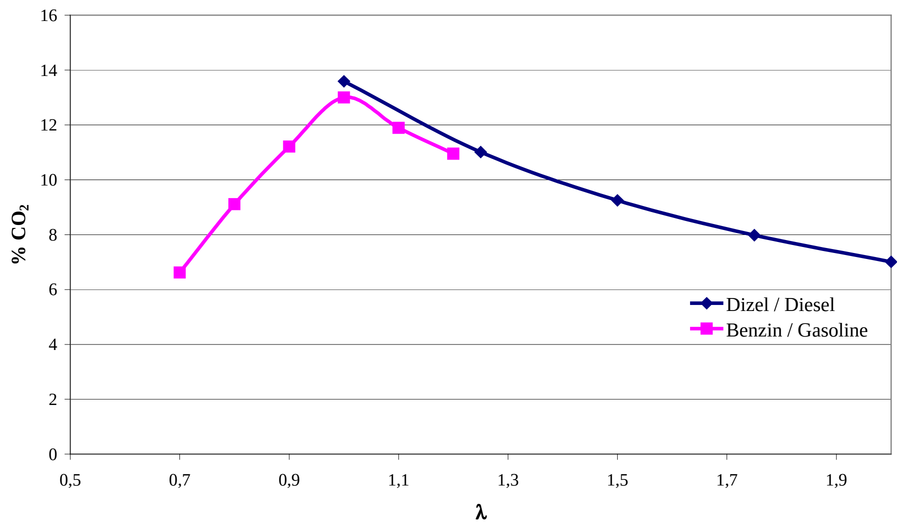
$$k = n + \frac{m}{4} \qquad (2)$$

U realnim uvjetima izgaranja koncentracija CO_2 u ispušnim plinovima MUIZ ovisi prije svega o omjeru zrak/gorivo i o vrsti goriva, što prikazuje slika 1, kao primjer za benzin i dizelsko gorivo.

λ - relativni omjer zrak/gorivo je definiran izrazom:

$$\lambda = \frac{\frac{m_a}{m_f}}{\left.\frac{m_a}{m_f}\right|_{stoich}} \qquad (3)$$

Slika 1: Ovisnost koncentracije CO_2 u produktima izgaranja o stehiometrijskom omjeru zrak/gorivo
Figure 1: Diesel and gasoline exhaust CO_2 concentration dependence on equivalence air/fuel ratio



Iz izraza (1) slijedi omjer za ocjenu emisije CO_2 nazvan **maseni indeks emisije**:

$$e_m = \frac{masa\ CO_2\ u\ produktima\ izgaranja\ [kg\ CO_2]}{1\ kg\ goriva\ \text{(reaktant)}} \qquad (4)$$

Kod čistih monokomponentnih fosilnih goriva indeks masene emisije CO_2 ovisi o **strukturi C_nH_m molekule** odnosno o broju C-atoma u molekuli goriva.

Za određivanje emisije CO_2 iz utrošene količine goriva povoljno je koristiti **volumetrijski indeks emisije CO_2:**

$$e_l = \frac{masa\ CO_2}{volumna\ jedinica\ goriva} = e_m \cdot \rho_g \qquad (5)$$

Za izračun emisije CO_2 iz motornih prijevoznih vozila (goriva smjese ugljikovodika) primjenjuje se **indeks emisije**:

$$e_s = \left[\frac{g\ CO_2}{km}\right] \qquad (6)$$

određen testiranjem vozila na ispitnom uređaju proizvođača po standardiziranom postupku, koji simulira režim vožnje, uz istodobno mjerenje, registriranje i obradu svih relevantnih parametara stanja pogonskog motora i vozila. Cijeli postupak testiranja vozila je definiran određenim standardom (npr. NEDC – Novi europski ciklus vožnje) i između indeksa emisije e_s i utroška goriva g_s postoji međusobna ovisnost, izražena kao:

$$K_Z \approx C \cdot \frac{e_S}{g_S}\left[\frac{kg\ CO_2}{dm^3\ goriva}\right] \qquad (7)$$

gdje je K_Z **emisijski faktor**. Ako se e_s izrazi kao [g CO_2/km], a g_s u [dm^3/100 km], $C=10^{-1}$ je konstanta.

Po faktorima K_Z i e_m vrijedi također sljedeća relacija:

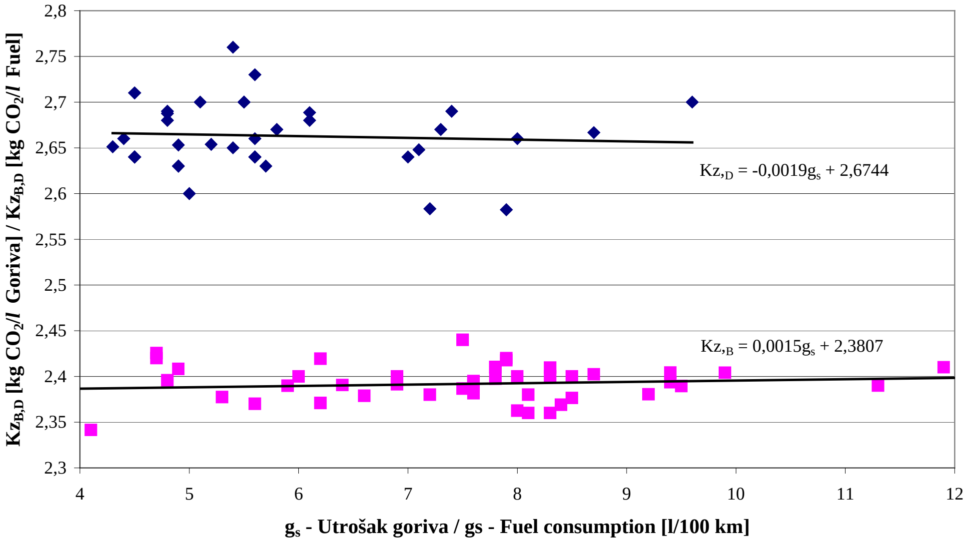
$$e_m = K_Z \cdot \frac{1}{\rho_g} = \left[\frac{kg\ CO_2}{kg\ gor}\right] \qquad (8)$$

gdje je ρ_g – gustoća goriva [kg/l], [kg/m^3].

Na slici 2 prikazane su kao diskretne tačke prosječne standardne vrijednosti za e_s pri utrošku goriva g_s suvremenih osobnih automobila, europskih, japanskih i drugih proizvođača automobila [2,3,4,5]. Dve regresijske prave izražavaju ovisnost emisijskog faktora K_Z za oba goriva, $K_{ZB} = f(g_{sB})$ i $K_{ZD} = f(g_{sD})$.. Integriranjem ova dva izraza prikazanih na slici 2, možemo odrediti prosječnu vrijednost emisijskog faktora realnih motornih goriva u području izabranih graničnih vrijednosti specifične potrošnje goriva putničkih vozila:

$$\overline{K_Z} = \frac{1}{g_{s1} - g_{s2}} \int_{g_{s2}}^{g_{s1}} K_Z(g_s) dg_s \qquad (9)$$

Slika 2: K_Z faktor emisije CO_2 benzina i dizelskog goriva
Figure 2: Gasoline and diesel fuel emission factor K_Z



Uvrštavanjem izraza ovisnosti K_{ZB} sa slike 2, za benzin dobijemo:

$$\overline{K_{ZB}} = \frac{1}{g_{s1} - g_{s2}} \int_{g_{s2}}^{g_{s1}} (0,0015 g_s + 2,3807) dg_s \qquad (10)$$

i K_{ZD} za dizelsko gorivo:

$$\overline{K_{ZD}} = \frac{1}{g_{s1} - g_{s2}} \int_{g_{s2}}^{g_{s1}} (-0,0019 g_s + 2,6744) dg_s \qquad (11)$$

Integracijom izraza (10) i (11) uz odgovarajuće algebarske radnje, izračunate su prosječne vrijednosti e_l, a izrazom (8) i e_m za područje g_{s1} = 10 i g_{s2} = 3 [l/100 km].

Za neka plinovita i tekuća čista monokomponentna i višekomponentna motorna goriva, izrazima (1), (5), (10) i (11) izračunati su indeksi e_m i e_l i rezultati prikazani u tablici 2.

Tablica 2: Indeksi specifične emisije CO_2 monokomponentnih i višekomponentnih motornih goriva
Table 2: Specific CO_2 emission indexes of mono and multiple component vehicle fuels

Gorivo / Fuel	Masa goriva / Fuel mass [kg]	Masa CO_2 / CO_2 mass [kg]	e_m	ρ_{gor} *	e_l **
Metan–zemni plin / Methane–CNG (CH_4)	16	44	2,75	0,7168	1,9712
Propan / Propane C_3H_8	44	132	3,0	1,96	5,88
n-Butan / n-Butane C_4H_{10}	58	476	3,03	2,668	8,08
Oktan / Octane C_8H_{18}	114	352	3,088	0,75	2,316
Benzin / Gasoline $C_{8,26}H_{15,5}$	114,62	363,44	3,17	0,75	2,378
Dizelsko gorivo / Diesel $C_{10,8}H_{18,7}$	148,3	475,2	3,204	0,83	2,659
Metanol / Methanol CH_3OH	32	44	1,375	0,729	1,00
Etanol / Ethanol C_2H_5OH	46	88	1,91	0,79	1,5
Metilni ester repičinog ulja / Rape's methyl ester	296	836	2,82	0,88	2,48
Motorni benzin / Automotive gasoline	-	-	3,187	0,72-0,75	2,39
Motorni dizel / Automotive diesel	-	-	3,207	0,83-0,87	2,66

* - $\rho_{metan,\ propan,\ butan\ /\ methane,\ propane,\ butane}$ [kg/m^3], ostalo / other [kg/l]
** - $e_{l\ metan,\ propan,\ butan\ /\ methane,\ propane,\ butane}$ [kg CO_2/m^3], ostalo / other [kg CO_2/l]

3. Trend smanjenja emisije CO_2 (e_s) prijevoznih vozila

Dogovorom predstavnika europske automobilske industrije VDA (Verband der Deutschen Automobilindustrie), ACEA (European Car Manufacturing Association), vladinih institucija unutar EU i drugih zaključeno je, da se u sklopu rješavanja globalnih ekoloških problema testirane vrijednosti standardne potrošnje (g_s) a time i emisije CO_2 (e_s) novoproizvedenih osobnih vozila poslije 1995. godine postupno smanjuju bez smanjenja efektivne snage pogonskog motora, primjenom obilatog potencijala inovacija i optimizacija pogonskog sustava i konstrukcije vozila. Na široj razini se strategija zaštite okoliša, proklamirana automobilskom industrijom, zasniva na primjeni telekomunikacijske tehnologije i telematike, s ciljem smanjenja prometne gužve, kako bi se uvođenjem kvalitetnih maziva i goriva, pneumatike s niskim koeficijentom trenja i alternativnih pogonskih sustava još više smanjila potrošnja goriva.

Drugi isto tako značajan, element ove strategije jest promoviranje povećanja udjela vozila s dizelovim motorom, koji u usporedbi s vozilom s benzinskim motorom ima manju specifičnu potrošnju goriva.

Rezime prijedloga VDA, ACEA odnosno trend TRIMOD [6] prikazan je u tablici 3.

Tablica 3: Prikaz postupnog smanjenja specifične emisije CO_2 i standardnog utroška goriva flote osobnih vozila
Table 3: Scenario of gradually reduction of CO_2 specific emission and standard fuel consumption of the new car fleet

Godina / Year	Specifična emisija CO_2 / Specific CO_2 emission		Standardni utrošak goriva / Standard fuel consumption [l/100 km]	
	[g CO_2/km]	Smanjenje / Reduction [%]	Benzin / Gasoline	Dizel / Diesel
1995.	186	-	7,8	7,0
2003.	165	11,3	7,0	6,0
2008.	140	24,7	5,8	5,3
2020.	120	14,3	4,9	4,5

4. Mogućnosti smanjenja emisije CO_2

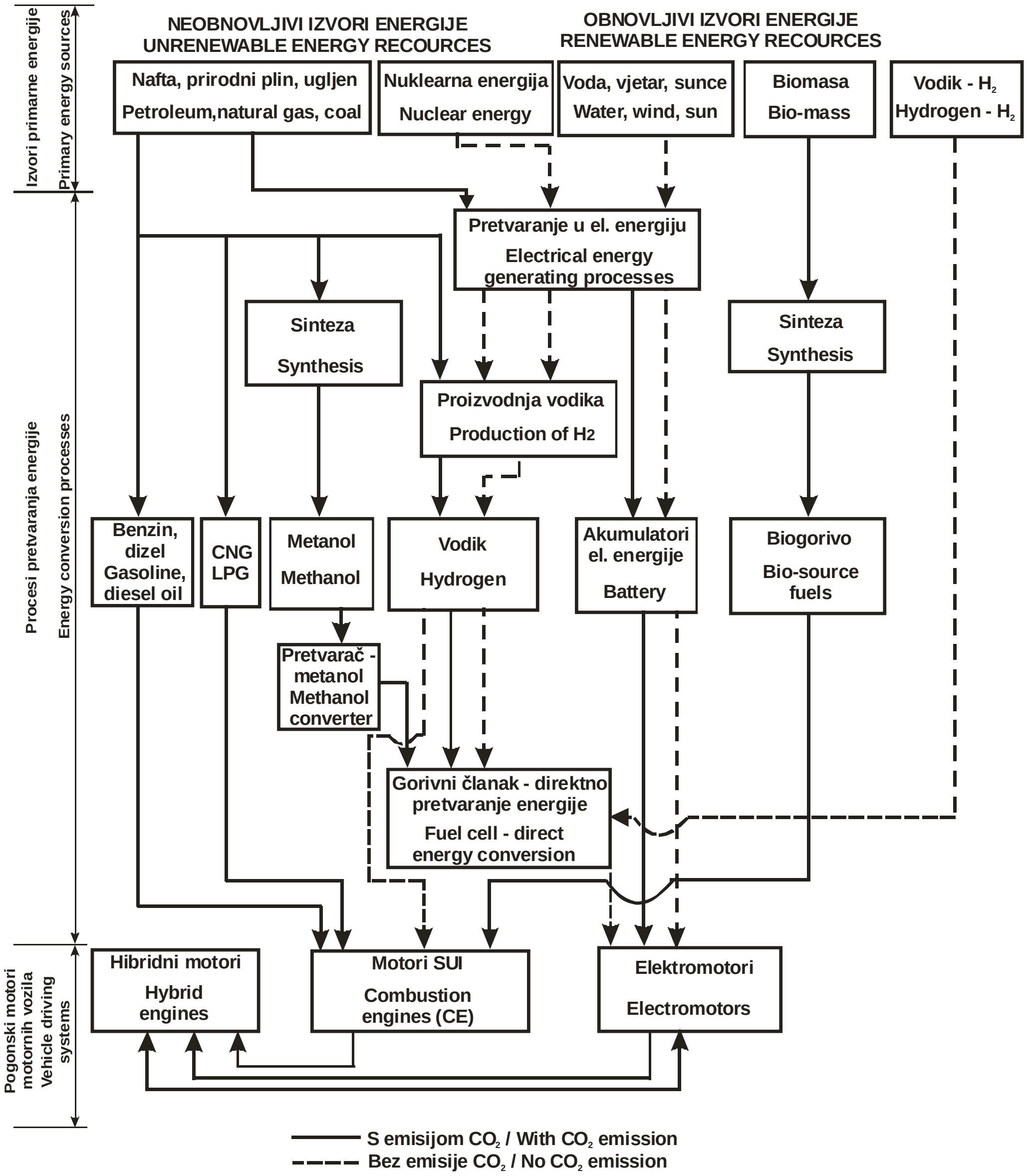
4.1. Utjecaj procesa konverzije primarne energije goriva

Procesi i mogući putevi pretvorbe primarne energije goriva u mehanički rad pogonskih motora prijevoznih vozila shematski su prikazani na slici 3. Kod nekih izvornih goriva lanac procesa u motoru obuhvaća i pripremu goriva u takav oblik, koji je pogodan za primjenu u motoru. Kod tih procesa dolazi već u toj fazi do stvaranja CO_2 (npr. uporaba CH_4 s međusintezom u gorivnom članku). Općenito pretvaranje primarne energije može biti posredno, uvjetovano termodinamičkim ciklusom (Ottov, dizelov), ili neposredno, kao što je proces konverzije energije H_2 u električnu u gorivnim člancima. Za primjenu električne energije za pogon vozila za sada prevladava indirektni put s punjenjem akumulatorske baterije iz električne mreže, s prethodnim pretvaranjem primarne energije u električnu u termo (nuklearnim) odnosno hidroelektranama. Ostali izvori energije (vjetar, sunce) imaju za smanjenje emisije CO_2 prijevoznih vozila za sada tek potencijalni značaj, dok biogoriva, pogotovo u smjesi s dizelskim gorivom pružaju određene mogućnosti ako se riješe problemi sirovine za masovnu proizvodnju motornog bio-dizela.

U tablici 4 je kao primjer prikazan utjecaj motornih goriva i procesa konverzije primarne energije tih goriva na ekvivalentni utrošak goriva i emisiju CO_2. [7] Pri razmatranju podataka u koloni 3 tablice 4 za punjenje akumulatora navedena je ekvivalentna energija. To je primarna energija izvornog goriva umanjena za gubitke konverzije te energije u električnu (gubici u termoelektrani, prijenosnoj mreži), kojom punimo akumulator.

Utjecaj na emisiju CO_2 danas najviše korištenih fosilnih goriva, benzina i dizelskog goriva u prvoj je fazi ovisan o stupnju iskorištenja goriva u motoru i ukupnom stupnju iskorištenja prijevoznog vozila u prometu. Prosječne vrijednosti efektivnog stupnja iskorištenja suvremenih automobilskih motora sa svom pripadajućom opremom, za benzinski motor (s prinudnim paljenjem smjese) se kreću od 30–35%, a za dizelove motore 38–43%. U tom omjeru su izmjereni i specifični utrošci goriva [g/kWh], odnosno za vozila [l/100 km].

Slika 3:Procesi konverzije primarne energije goriva
Figure 3: Fuel primary energy conversion processes



Tablica 4: Usporedba emisija CO_2 i ekvivalentnih iskorištenja primarne energije u pogonskim motorima vozila
Table 4: The comparison of CO_2 emissions and equivalent fuel economy of primary energy conversion paths applied in vehicle driving systems

Sustav pogona vozila / Vehicle diving system	Korišteno gorivo / Fuel used	Primarna energija goriva / Primary fuel energy [kJ/l]	U toku vožnje / On the road		
			Utrošena primarna energija / Consumed primary energy [kJ/km]	Ekvivalentan utrošak / Equivalent consumption [l/100 km]	Relativna emisija CO_2 / Relative CO_2 emission [g/km]
1	2	3	4	5	6
Hibridni pogon / Hybrid system	dizelsko gorivo / diesel	35690	1311	3,7	106
Gorivni članci / Fuel cell (H_2)	metan / methane	37920 *(1)	1255	3,3	116
Dizelov motor / Diesel engine	dizelsko gorivo / diesel	35690	1560	4,4	131
Plinski motor (s prinudnim paljenjem smjese) / Gas engine (with spark ignition)	metan / methane	37920 *(1)	1657	4,4	134
Gorivni članci (sinteza → metanol → H_2) / Fuel cell (synthesis → methanol → H_2)	benzin / gasoline	32412	1585	4,9	153
Otto motor / Petrol engine	benzin / gasoline	32250	1635	5,1	163
Električni akumulator / Electric accumulator	prirodni plin / CNG	21960 *(1)	1000	4,55 *(2)	-
	ugljen/coal	7759 *(3)	1000	12,9 *(4)	-

* (1) [kJ/m^3], (2) [m^3 plina/ 100 km], (3) [kJ/kg], (4)) [kg ugljena/ 100 km]

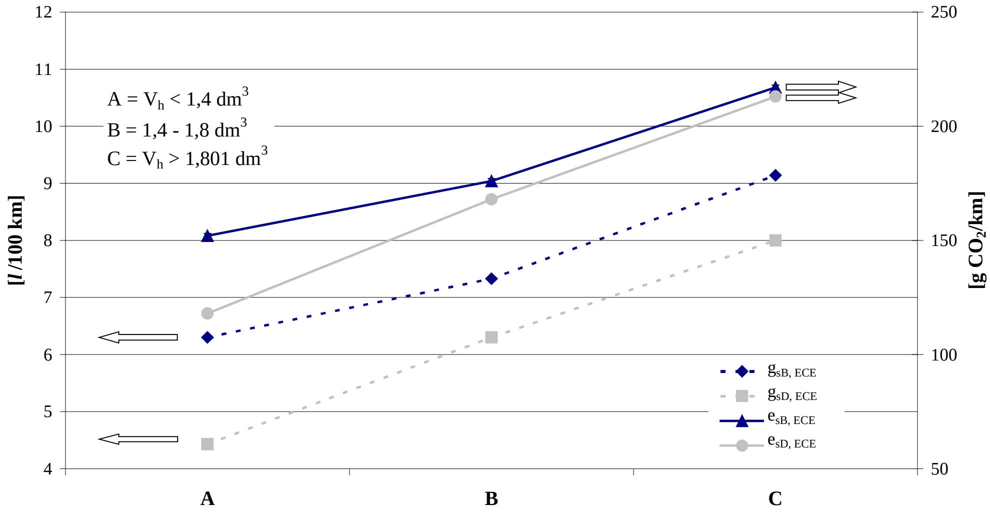
Na slici 4 su prikazane prosječne vrijednosti standardnih specifičnih utrošaka vozila s benzinskim (g_{sB}) ili dizelovim motorom (g_{sD}), (indeks "ECE"). Statistički uzorak je imao u svakoj grupi vozila vrijednosti (g_s) od ukupno 25% godišnje registriranih vozila (cca. 250.000 vozila) od 180 modela 12 proizvođača osobnih vozila, čija je prisutnost na tržištu bila veća od 3%.

Ovisno o prosječnim vrijednostima standardnih utrošaka goriva, izračunati su indeksi emisije svake grupe vozila e_s [g CO_2/km], pomoću izraza (12) i (13), dobivenih primjenom definicije (7) i izraza za $K_{ZB} = f(g_{sB})$ i $K_{ZD} = f(g_{sD})$ na slici 2.

$$e_{sB} = 9{,}074 + 22{,}73 \cdot g_{sB} \left[\frac{g\ CO_2}{km} \right] \qquad (12)$$

$$e_{sD} = 0{,}5 + 26{,}56 \cdot g_{sD} \left[\frac{g\ CO_2}{km} \right] \qquad (13)$$

Slika 4: Usporedba prosječnih vrijednosti za razdoblje 1992. – 2003. specifičkih utrošaka i odgovarajućih indeksa emisije grupa automobila (deklarirane vrijednosti) s benzinskim (B) i dizelovim (D) motorom
Figure 4: Comparison of average specific fuel consumptions and corresponding emission indexes (manufacturer values) of vehicle group of gasoline (B) and diesel (D) engine for the period 1992 – 2003



4.2. Utjecaj kakvoće goriva

Kakvoća goriva je definirana fizikalnim i kemijskim značajkama goriva, sadržajem štetnih primjesa i aditiva i oduvijek je upravljala razvojem i eksploatacijom MUIZ te utjecala na razvoj zaštite zraka. O utjecaju kakvoće na performance MUIZ i na okoliš opširno je prikazano i raspravljeno u literaturi [11].

U pogledu emisije CO_2 iz prijevoznih sredstava, visoka kakvoća motornih goriva ima povoljan utjecaj na fizikalnu i kemijsku fazu procesa izgaranja, doprinoseći povećanju termodinamičkog stupnja iskorištenja ciklusa motora te u velikoj mjeri doprinosi ekonomičnom utrošku goriva. Fizikalna svojstva motornih goriva (gustoća, viskoznost, površinska napetost, T50, omjer C/H i dr.) utječu na fizikalne procese pripreme smjese, kao: atomizaciju i penetraciju mlaza, isparavanje i miješanje para goriva i zraka, dok kemijske značajke, primjese, aditivi utječu na mehanizam i kinetiku kemijskih reakcija, a time i na tijek izgaranja, karakteristiku oslobađanja topline, na stupanj iskorištenja unutrašnje energije goriva i sastav produkata izgaranja uključujući emisiju CO_2.

Upotreba bio-alternativnih goriva u pogonskim sustavima transportnih vozila, imat će važnu ulogu u smanjenju emisije CO_2 u prijelaznom periodu, a H_2 kao goriv u buduće.

U posljednih deset godina učinjen je veliki napredak u razvoju autobusa pogonjenih gorivnim člankom, koji su već u javnom prometu u više gradova širom svijeta, što čini vrlo važnu prekretnicu u smanjenju CO_2 u atmosferi.

U okviru rasprave o kakvoći motornih goriva s obzirom na emisiju CO_2 potrebno se osvrnuti i na direktnu primjenu vodika u kombinaciji s gorivnim člankom (slika 3 – crtkana linija) u pogonskom sustavu prijevoznih vozila, s konačnim ciljem da u dogledno vrijeme zamijene MUIZ.

Razvoj i planiranje tehnologije gorivnog članka i masovno uvođenje H_2 – vozila u cestovni promet sa ciljem da se značajno smanji emisija CO_2, očigledno su suočeni s većim brojem vrlo ozbiljnih problema. Spomenimo ukratko samo osnovne:

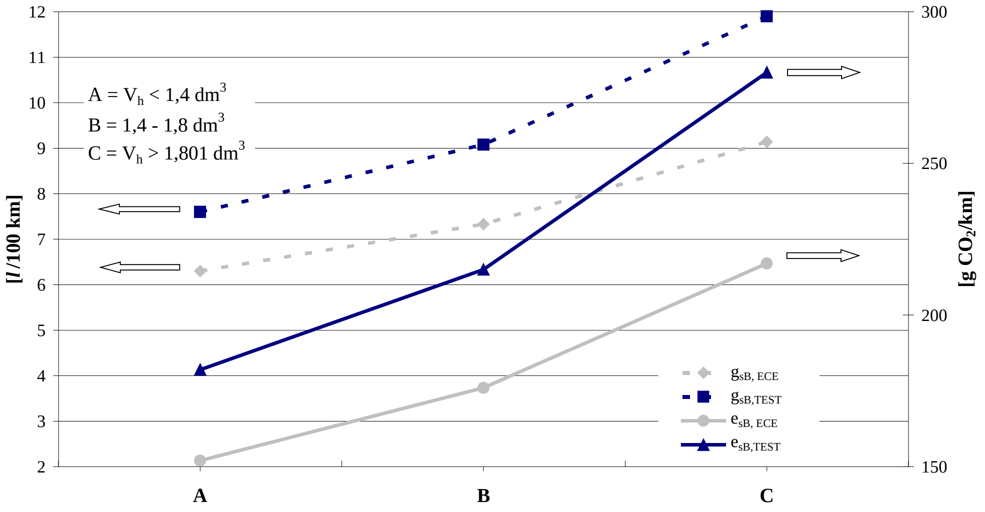
1. Izgradnja **infrastrukture za distribuciju H_2** koja uključuje uskladištenje, prijevoz i punjenje prijevoznih vozila s tekućim vodikom. Prema objavljenim podacima vodik je u prvoj fazi korištenja raspoloživ u dovoljnoj količini, kao sporedni produkt u kemijskoj industriji. Za prijevoz i uskladištenje tekućeg H_2 (pri -253℃) su potrebni skupi kriogeni rezervoari iz nehrđajućeg čelika. Predviđa se da će troškovi izgradnje infrastrukture u Europi iznositi minimum 10 – 20 milijardi €.
2. **Punjenje vozila** na prodajnim mjestima zbog istih razloga, zahtijeva glomaznu toplotno odlično izoliranu instalaciju, tako da će najvjerojatnije samoposluživanje vozača morati biti isključeno i da će cjelokupan postupak punjenja biti robotiziran i zbog samog skraćenja vremena punjenja.
3. **Pogonski troškovi** (cijena goriva i održavanja vozila) danas su još ogromni, po ocjeni 8 do 10 puta veći [12]. To zahtijeva ubuduće velika ulaganja u razvoj novih tehnologija, uporaba novih jeftinijih materijala i tehnoloških postupka izrade i produkcije, da bi se oni smanjili na prihvatljivu razinu troškova.
4. **Pouzdanost** pogonskog sustava u prometu još ne može konkurirati MUIZ koji za sobom imaju više od 100 godina razvoja i korištenja u vozilima.

Uporaba alternativnih goriva u kombinaciji s hibridnom tehnologijom pogonskih sustava prijevoznih vozila mogla bi poslužiti kao most za prijelaz na primjenu gorivnih članaka. Bio-goriva pružaju više pogodnosti u pogledu globalnog smanjenja emisije CO_2, ali njihova uporaba je već ograničena zbog nedovoljne količine biogoriva na tržištu. U tom pogledu bi sintetička biogoriva, kao npr. SunDiesel, mogla imati značajnu ulogu ubuduće. Gorivo SunDiesel (biomass – to – liquid, BTL fuel) sa svojim je visokim potencijalom smanjenja CO_2, koji iznosi i do 90%, znatno superiornije od biogoriva iz uljne repice. Goriva iz biomase mogu pridonijeti smanjenju ispuštanja u atmosferu fosilnog CO_2. Neka predviđanja nagovještavaju da 20%-tni udjel biogoriva na tržištu može značajno smanjiti emisiju CO_2 u cestovnom prometu.

4. 3. Utjecaj okoline

Utjecaj okoline na emisiju CO_2 prijevoznih vozila u uvjetima cestovnog prometa, vrlo je kompleksan i uključuje veliki broj faktora koji utječu na kakvoću vožnje. Ova ovisi o ponašanju (psihičkom stanju) vozača, njegove (njezine) starosti i vozačkog iskustva, gustoći, konfiguraciji i kvaliteti cestovne infrastrukture, geografskih značajki teritorija, ako navedemo samo najvažnije. Kao rigoroznu posljedicu ovih utjecaja možemo smatrati povećanje utroška goriva u usporedbi sa standardnim. Da bi kvantificirali utjecaj cestovnog prometa na emisiju CO_2 prijevoznih vozila, mjerili smo cestovne utroške goriva ($g_{s,TEST}$) i odredili prosječnu vrijednost za grupu, te je usporedili s prosječnom vrijednošću standardnog utroška goriva ($g_{s,ECE}$) iste grupe vozila. Distribucija grupa vozila (*A,B,C*) je temeljena na stapajnom volumenu motora, što je napomenuto prije. Rezultati testiranja se odnose na osobna vozila, koja su bila na tržištu između 2001. – 2004. godine. CO_2 emisije grupe vozila su određene računski po izrazima (12) i (13). Rezultati su prikazani na slici 5.

Slika 5: Usporedba prosječnih deklariranih i cestovnih specifičnih utrošaka goriva i emisije CO_2 grupa osobnih automobila s benzinskim motorom (V_h - stapajni volumen motora)
Figure 5: Comparison of average declared and road specific fuel consumption and CO_2 emission of passenger vehicle group with gasoline engine (V_h –engine displacement volume)



Prosječna vrijednost utroška goriva u prometu ($g_{s,TEST}$) svake grupe osobnih vozila temelji se na statističkom uzorku od oko 100 testiranih vozila. Razliku između cestovnog i standardnog utroška goriva i odgovarajućih CO_2 emisija osobnih vozila, koja prikazuje učinak okoline, potrebno je promatrati samo kao ocjenu učinka, zbog vrlo jakog utjecaja lokalnog ljudskog faktora i lokalnih uvjeta cestovnog prometa na izmjerene vrijednosti prilikom testiranja vozila ($g_{sB,TEST}$), kao i zbog relativno "malog" statističkog uzorka. Podaci su ponovno obrađeni i u vidu relativnih vrijednosti prikazani posebno za svaku grupu osobnih vozila u tablici 5. Uspoređene vrijednosti ukazuju na signifikantan učinak pogonskog motora osobnog vozila (ekonomičnosti izgaranja; B, D), posredno vrste goriva, te cestovnog prometa (TEST/ECE) na emisiju CO_2.

Tablica 5: Podaci o relativnim emisijama CO_2 osobnih vozila s benziskim i dizelovim motorom

Table 5: Relative CO_2 emission data of cars with petrol and diesel engines

Benzinski motor Petrol engine				Standard (ECE)	Dizelov motor Diesel engine				TEST
Grupa Group	Specifična energija Spec. power [kW/dm^3]	Spec. emisija Spec. emission [g CO_2/km kW]		$\dfrac{\left.\frac{g\,CO_2}{km\,kW}\right\vert_B}{\left.\frac{g\,CO_2}{km\,kW}\right\vert_D}$	Grupa Group	Specifična energija Spec. power [kW/dm^3]	Spec. emisija Spec. emission [g CO_2/km kW]		$\dfrac{\left.\frac{g\,CO_2}{km\,kW}\right\vert_B}{\left.\frac{g\,CO_2}{km\,kW}\right\vert_D}$
		ECE	TEST				ECE	TEST	
1	2	3	4	5	6	7	8	9	10
A	43,7	2,7	3,2	1,2	A	38,9	2,2	2,7	1,19
B	50,7	2,1	2,6	1,05	B	44,5	2,0	2,4	1,08
C	55,4	1,8	2,3	0,95	C	44,5	1,9	2,3	1,0

5. Zaključak

Razmatrali smo osnovna gledišta emisije CO_2 prijevoznih vozila:

1. utjecaj motornih goriva,
2. ovisnost pretvorbe primarne energije goriva u motoru s unutarnjim izgaranjem odnosno u pogonskom sustavu vozila,
3. utjecaj "okoline" definirane kao učinak cestovnog prometa i ocijenjen s utroškom goriva prilikom testiranja.

Ad. 1: Masa CO_2 u ispušnim plinovima MUIZ je direktno proporcionalna masi ugljikovodičnog goriva, koji izgara pod stehiometrijskim uvjetima. Omjer obiju masa je **definiran kao maseni indeks emisije CO_2 e_m**. Izračunate su vrijednosti CO_2 emisija monokomponentnih motornih goriva i one su od 2,75 do 3,2 [kg CO_2/1 kg goriva]. Masene indekse CO_2-emisije višekomponentnih smjesa C_nH_m, kao što su benzin i dizelsko gorivo smo odredili pomoću relacija za emisijski faktor K_Z (slika 2). Prosječne vrijednosti e_m za benzin su 3,18 i za dizelsko gorivo 3,21[kg CO_2/1 kg goriva].

Rapravljeno je o **sporazumu europskih proizvodjača automobila**, da se u cilju smanjenja emisije CO_2 postupno smanjuje standardni utrošak goriva novih automobila proizvedenih u razdoblju 1995. – 2020. godine i prikazano u tablici 3. Između alternativnih motornih goriva smo razmotrili goriva iz biomase i gorivo H_2, te njihove prednosti u pogledu smanjenja emisije CO_2, kao i probleme u opskrbi tržišta.

Ad. 2: Razmotrili smo moguće puteve **konverzije primarne energije goriva** u mehaničku energiju u pogonskim sustavima prijevoznih vozila. Kvantificirali smo i usporedili ekonomičnost i CO_2 emisiju nekoliko motora koji se koriste za pogon prijevoznih vozila. Grafički su prikazane statističke prosječne vrijednosti standardnih utrošaka goriva i odgovarajučih CO_2 emisija za tri grupe automobila.

Ad. 3: Da bismo ocijenili **kompleksni utjecaj okoline na CO_2 emisiju** prijevoznog vozila, prihvaćen je postupak mjerenja utroška goriva u uvjetima cestovnog prometa. Ispitan je veći broj vozila, podijeljenih u grupe prema stapajnom volumenu motora i prezentirani su podaci, koji ukazuju na povećanje utroška goriva i emisija CO_2. Doprinos cestovnog prometa specifičnim emisijama [g CO_2/km kW] (tablica 5) osobnih vozila se ocjenjuje od 18 (grupa A) do 25% (grupa C) za automobile s benzinskim motorom i oko 20% za sve tri grupe automobila s dizelovim motorom. Specifične emisije CO_2 automobila s benzinskim motorom su do 19% veće, kao što je prikazano u kolonama 5 i 10 tablice 5.

VEHICLE FUEL COMBUSTION CO_2 EMISSION

Abstract

The aim of this paper is to evaluate the contribution of vehicular fuel and IC engines on CO_2 emission. Definitions of mass and volumetric emission indexes and emission factor are given, and the calculated values for mostly used C_nH_m fossil fuels are presented. The scenario of European carmaker voluntary agreement to reduce the specific CO_2 emission [g CO_2/km] over the years 1995 through 2020 is discussed. The role of fuel energy conversion process in vehicle engines is analyzed and its effect on fuel consumption [l/100 km] and CO_2 emission is summarized. Average values of standardized (ECE) and road (test) fuel consumption performances of vehicles with SI engines have been calculated and associated CO_2 emissions are presented. The requisite approaches to reduce vehicle CO_2 emission are discussed.

1. Introduction

From the total global CO_2 emissions, only around 3 per cent are attributable to the human activities, and road vehicles contribute today a mere 12 per cent to these anthropogenic emissions. Distribution of anthropogenic CO_2 emissions is presented in Table 1. During the last 15 years this proportion has changed significantly especially in countries with rapid economic development, growing road transport of people and goods, with increasing traffic density in urban area and highways and several other reasons. This causes a growth of fuel consumption and CO_2 emissions respectively.

Road traffic plays a central role today in satisfying society's demands for mobility because of its systematic properties, such as flexibility and permanent availability. Technical innovation route is the basic concept of climate protection policy accepted by automotive industry, with the main goal to decrease economic environment protection costs. It has been demonstrated, for example, that the technical costs incurred in avoiding an extra ton of CO_2 emissions from a road vehicle are around three to eight times more, than costs of CO_2 reduction by technical means implemented in several fields of industry, power plants and private households [1]. The reduction of motorized road vehicle CO_2 emission can be essentially reduced:

- by optimizing the combustion process, operating engine parameters including exhaust gas after treatment devices, operating vehicle driving system characteristics, all measures are taken to minimize the fuel consumption (g/kWh, l/km);

- by applying fuels with poor carbon content (C/H/O ratio, blends and emulsions), bio-fuels, zero carbon fuels, like H_2.

Pursuing this requirement significant, even strategic role is associated with:

- automotive fuel industry to further improve the fuel quality and oil processing technology, modernizing the refineries and infrastructure to offer several kinds of engine fuels, their blends and emulsions in required quantities,
- automotive industry with innovative development and high quality production of engines and transport vehicles,
- society with environmental friendly legislation, economic, financial and fiscal policy.

2. Parameters to evaluate transport vehicle CO_2 emissions using hydrocarbon fuels

In the internal combustion (IC) engine exhaust gases, CO_2 and water vapor are contained in a high percentage. Complete combustion of C_nH_m mono component fuel under stoichiometric combustion may be described with:

$$C_nH_m + k \cdot O_2 + 3{,}76 \cdot k \cdot N_2 \rightarrow n \cdot CO_2 + \frac{m}{2} \cdot H_2O + 3{,}76 \cdot k \cdot N_2 \qquad (1)$$

where designates:

$$k = n + \frac{m}{4} \qquad (2)$$

Under real conditions IC engine exhaust gas CO_2 concentration depends basically on the air/fuel ratio, and on the kind of fuel. In the Figure 1, this dependence of CO_2 concentration on air/fuel ratio is presented by two curves, related to petrol and diesel fuel combustion in an IC engine.

λ - the equivalence air/fuel ratio is defined by:

$$\lambda = \frac{\dfrac{m_a}{m_f}}{\left.\dfrac{m_a}{m_f}\right|_{stoich}} \qquad (3)$$

Using expression (1), the CO_2 **mass emission index** may be defined by:

$$e_m = \frac{CO_2\ mass\ in\ combustion\ products\ [kg\ CO_2]}{1\ kg\ fuel\ \text{(reactant)}} \qquad (4)$$

The CO_2 mass emission index of pure mono component fossil fuels is dependant on **C_nH_m molecule structure**, i.e. on the number of C atoms in the fuel molecule.
To calculate CO_2 emission from the amount of fuel burnt, it is more convenient to use **CO_2 volumetric emission index**, defined by:

$$e_l = \frac{CO_2\ mass}{fuel\ volume\ unit} = e_m \cdot \rho_g \qquad (5)$$

To evaluate CO_2 emission of the automotive transport vehicles burning mixtures of multicomponent hydrocarbons the CO_2 **emission index** is used, defined by:

$$e_s = \left[\frac{g\ CO_2}{km}\right] \qquad (6)$$

The values of e_s are obtained by vehicle testing on the carmaker's test rig under standard conditions, simulating driving regimes, by simultaneously monitoring and processing all relevant operating parameters of engine and vehicle. The vehicle test cycle is standardized (for example NEDC) and CO_2 road emission index e_s depend on vehicle specific fuel consumption g_s. Relating both vehicle parameters the **CO_2 emission factor K_Z** may be defined:

$$K_Z \approx C \cdot \frac{e_S}{g_S}\left[\frac{kg\ CO_2}{l\ goriva}\right] \qquad (7)$$

If e_s is [g CO_2/km] and g_s is [l/100 km] the constant is $C = 10^{-1}$.

Between CO_2 emission factor K_Z and CO_2 mass emission index the following relation exists:

$$e_m = K_Z \cdot \frac{1}{\rho_g} = \left[\frac{kg\ CO_2}{kg\ gor}\right] \qquad (8)$$

where ρ_g is the fuel density [kg/l], [kg/m^3].

In Figure 2 the average standard values of e_s in relation with g_s of new cars presented by European, Japanese and other carmakers [2,3,4,5] are introduced as discrete values and correlated by two regression straight lines, expressing the relation between $K_{ZB} = f(g_{SB})$ and $K_{ZD} = f(g_{SD})$ of petrol and diesel engined test cars.

By integration of both expressions presented in Figure 2, the average value of emission factors between prescribed limits of car specific fuel consumption may be obtained

$$\overline{K_Z} = \frac{1}{g_{s1} - g_{s2}} \int_{g_{s2}}^{g_{s1}} K_Z(g_s)\,dg_s \qquad (9)$$

Introducing the gasoline K_{ZB} straight line relation, we have:

$$\overline{K_{ZB}} = \frac{1}{g_{s1} - g_{s2}} \int_{g_{s2}}^{g_{s1}} (0{,}0015 g_s + 2{,}3807)\,dg_s \qquad (10)$$

and the same for diesel fuel

$$\overline{K_{ZD}} = \frac{1}{g_{s1} - g_{s2}} \int_{g_{s2}}^{g_{s1}} (-0{,}0019 g_s + 2{,}6744)\,dg_s \qquad (11)$$

By integration of the expressions (10) and (11) and by some algebraic computations the average values for e_l, and by applying the expression (8), the average values for e_m between the limits g_{s1} = 10 and g_{s2} = 3 [*l*/100 km] have been calculated.

Using expressions (1), (5), (10) and (11) the e_m and e_l indexes for gas and liquid, single and multi component automotive fuels have been computed and the results are presented in Table 2.

3. Scenario of transport vehicle CO_2 emission (e_s) reduction

In order to contribute to reduction of global CO_2 level in the atmosphere, the European carmakers (at the level of ACEA, VDA), governments and other institutions within EU have agreed to cut the average standard fuel consumption and CO_2 emission respectively of new cars gradually by starting with the year 1995, by exploiting considerable potentials of innovations and optimizations of drive systems and vehicle layout, however with no reduction of effective engine power. Moreover, the automotive industry's climate protection strategy is based also on the use of telecommunication technologies, telematics to reduce traffic congestion, the application of engine oils and high quality fuels, low friction tires and alternative drive systems to further reduce fuel consumption.

Additionally another significant step of this strategy is the promotion of the proportion of diesel vehicles with better specific fuel consumption than comparable petrol powered vehicles.

The milestones of VDA, ACEA commitment – TRIMOD scenario [6] is presented in Table 3.

4. Potentials of the CO_2 emission reduction

4.1. The influence of primary energy conversion process

Possible paths of fuel primary energy conversion to mechanical energy of transport vehicle driving systems are schematically illustrated in Figure 3. The sequence of application of some of source fuels, shown in Figure 3 includes preliminary conversion of original fuel into fuel which is then further used in the engine. During this process CO_2 is formed (example: application of CH_4 via synthesis in fuel cell). Generally, the primary energy conversion may follow **indirect path via a thermodynamic (Otto, Diesel) cycle or direct path, like H_2 energy conversion in fuel cell**. To power vehicle driving system with electrical energy via accumulator (battery), the indirect path must be used with battery charging, and primary energy is preliminary converted to electrical energy in a thermo (nuclear), hydro power plant. Other energy sources (wind, solar energy) play in reduction of transport vehicle CO_2 emissions a secondary role today, while the biofuels also as diesel fuel blends have potentials to be used in vehicle driving systems if the problem of biofuel mass production will be solved satisfactorily.

The comparison of fuel primary energy conversion processes, equivalent fuel consumptions and CO_2 emissions in presented in Table 4. The data of the equivalent energy to charge engine batteries given in the column 3 in the Table 4 have been calculated by accounting all loses of fuel primary energy conversion to electrical energy in power plant and network grid.

The effect of today mostly used fossil fuels, especially gasoline and diesel fuel on vehicle CO_2 emissions is mainly dependant on the fuel conversion economy in engine and on the transport vehicle traffic efficiency. The average values of gasoline spark ignition engine brake thermal efficiency are around 30 – 35% and those of diesel, compression ignition engines are 38 – 43%. The engine effective fuel consumption [g/kWh], or vehicle fuel consumption [*l*/100 km] respectively are in agreement with the data of engine efficiencies.

The average of the standard fuel consumptions of vehicles with petrol (g_{sB}) and diesel engine (g_{sD}) are presented in Figure 4. Cars registered between 1992 – 2003 have been sorted, according to the engine displacement volume in three groups (A, B, C), and standard fuel consumptions have been calculated for each group separately. Statistical samples has contained in each group g_s values of around 25% of annually registered cars (cca. 250.000 cars), of 180 different models made by 12 car makers participating on the country market with more than 3%.

In relation with the standard vehicle fuel consumptions, the road emission indexes e_s [g CO_2/km] have been calculated for each car group by using expressions (12) and (13), which were obtained by interrelating definition (7) and expressions for K_{ZB} and K_{ZD} in Figure 2.

$$e_{sB} = 9{,}074 + 22{,}73 \cdot g_{sB} \qquad (12)$$

$$e_{sD} = 0{,}5 + 26{,}56 \cdot g_{sD} \qquad (13)$$

4.2. The effect of fuel quality

The quality of automotive fuels has been defined by physical and chemical properties, the content of blends and additives, and it has played a dominant role in transport vehicle IC engines development, application and air pollution. The effect of fuel quality on vehicle engine performance and on environment has been illustrated and discussed in detail in reference [11].

Concerning transport vehicle CO_2 emissions, high fuel quality has a beneficial effect on physics and chemistry of engine combustion process, contributing to increase of thermodynamic efficiency of engine cycle, influencing to a great deal the fuel economy. In general, petrol and diesel **fuel physical properties** (density, viscosity, surface tension, T50, C/H ratio) effect the fuel/air mixture formation, via droplet atomization, spray penetration, heating, evaporation and mixing of fuel vapors with surrounding air, while **chemical properties** govern mechanism and kinetics of chemical reactions, determining burning velocity, combustion characteristics, brake effective efficiency of thermodynamic engine cycle and exhaust products composition including CO_2 emissions.

The application of bio alternative fuels in transport vehicle driving systems may have an important role in reducing CO_2 emissions in medium term, and H_2 as the fuel in the future.

H_2 fuel cell technology has made a great progress during the last ten years and the development of the fuel cell buses, operating in public transport in various cities around the world has been an important milestone in recent years.

Within the frame of our discussion about automotive fuel quality in relation to CO2 emission, the direct application of H_2 – powered fuel cell (Figure 3 – hatched line) in transport vehicle driving system with the final goal to replace IC engines in the foreseeable future, has to be discussed.

The development and planning of fuel cell car technology and the introduction of H_2 – powered vehicles in road traffic and public transport in order to significantly reduce CO_2 emissions, are today confronted still with several great problems. Let us illustrate shortly just a few of them, however the most important ones only:

1. The building of **H_2 distribution infrastructure**, H_2 storing and refueling of transport vehicles with liquid hydrogen. According to published data is hydrogen readily available as the by-product in chemical industry. To transport and store the liquid hydrogen (at -253℃), expensive cryogeni c tanks made of stainless steel are needed. The cost to build complete hydrogen distribution infrastructure might be very high, and for Europe a sum of minimum €10 – 20 billions is estimated.
2. **Car refueling** with H_2 at service stations requires the bulky, heavily heat insulated refueling equipment and most probably human manipulation has to be eliminated and the whole refueling procedure will be robotized.

3. **Costs** (fuel and maintenance) are still very high, and thus it is estimated they are about 8 to 10 times higher of today's costs [12]. To reduce these costs immense investments in development of new technologies, less expensive materials and H_2 – car production procedures have to be introduced in automotive industry in the future.
4. **The reliability** of the vehicle driving system can still not compete with IC engines going through a hundred years development and application.

The use of alternative fuels combined with the hybrid technology may be a bridge to fuel cell. Biofuels offer several benefits, regarding reduction of CO_2 emissions, but the use of them is limited already because of their shortage on the fuel market. In this regard synthetic biofuels as SunDiesel may play remarkable role in the future. SunDiesel is a biomass – to – liquid (BTL) fuel and it has the highest CO_2 reduction potential, amounting more then 90 per cent and it is considerably superior to biodiesel from rapeseed oils. Biogenous fuels may help to decrease the release of fossil CO_2 into the atmosphere. Some estimations predict that market share of 20 per cent of biofuels could significantly reduce CO_2 emission from road traffic.

4.3 The impact of the environment

The effect of environment on transport vehicle CO_2 emissions under road traffic conditions is very complex, including a great number of factors influencing quality of driving. This depends on driver's behavior, vehicle age and maintenance, overall engine performance, road and infrastructure density and quality, territory geographic location and road configuration, if we list here just a few of them. The salient characteristics of these effects, the augmentation of vehicle fuel consumption may be considered as a consequence. For the purpose of quantification of road traffic influence on transport vehicle CO_2 emissions, the fuel consumption ($g_{s,TEST}$) has been measured and averaged and compared with the average value of standard fuel consumption ($g_{s,ECE}$) of the same vehicle group. Group distribution (A, B, C) is based on engine displacement volume. The test results have been carried out during years 2001 – 2004 and the results are presented in Figure 5. The CO_2 vehicle group emissions have been computed applying the expressions (12) and (13) and using the average values of g_{sB}.

The average value of vehicle road fuel consumption ($g_{s,TEST}$) of each vehicle group is based on a statistic sample of about hundred vehicles. The difference between road and standard fuel consumptions and associated CO_2 emissions, demonstrating the effects of environment, must be considered merely as estimation because of very strong influence of local infrastructure and road traffic conditions on data of vehicle testing as well as, because of the rather small volume of the statistic sample. The data are summarized and presented in Table 5, demonstrating the effect of car driving system, kind of fuel (B, D) and road traffic (TEST/ECE) on CO_2 emissions. The data are generalized and presented as relative values for each car group separately.

5. Conclusions

The main aspects of transport vehicle CO_2 emissions have been considered:

1. the effect of automotive fuels,
2. the influence of fuel primary energy conversion path in vehicle engine and driving system,
3. the impact of the environment, defined as road traffic effect and estimated by vehicle road test fuel consumption.

Ad. 1: The mass of CO_2 in the IC engine exhaust is directly proportional to the mass of hydrocarbon fuel burning under stoichiometric conditions. The mass ratio of both is **defined as the CO_2 emission index – e_m.** The e_m values of several mono component automotive fuels have been computed and the CO_2 emissions are 2,75 and 3,2 [kg CO_2/1 kg fuel] . The mass CO_2 emission indexes of multi component C_nH_m mixtures, as gasoline and diesel fuel has been obtained by applying CO_2 emission factor K_Z relations and the calculated values are appr. 3,18 for gasoline and 3,21 [kg CO_2/1 kg fuel] for diesel fuel.

The voluntary agreement of European carmakers to cut new car standard fuel consumption and to reduce CO_2 emissions respectively, between the years 1995 – 2020, has been discussed and the reduction scenario is presented. Among alternative automotive fuels, biofuels and H_2 have been considered and the advantages regarding CO_2 emission reduction as well as the problems of their use and market supply have been discussed.

Ad. 2: The possible paths of **fuel primary energy to mechanical energy conversion** in vehicle driving systems have been analyzed. The economy of energy use and the CO_2 emissions of several engines used today to power transport vehicles have been quantified and compared. The statistical data of the petrol and diesel powered passenger car standard fuel consumptions and the corresponding CO_2 emissions are presented graphically for three passenger car groups.

Ad. 3: To estimate the **complex impact of environment on transport vehicle CO_2 emissions**, the approach of vehicle fuel consumption identification under road traffic conditions has been chosen. A great number of vehicles, grouped according to engine displacement volume, have been tested and the results are presented, demonstrating the increase of fuel consumptions and corresponding CO_2 emissions. The contribution of the road traffic to the transport vehicle CO_2 relative emissions [g CO_2/km kW] may be estimated between 18 (group A) to 25 (group C) per cent, and the CO_2 emissions of petrol powered car are approximately up to 19 per cent higher (fuel economy) compared to diesel powered vehicle relative fuel consumption as presented in Table 5, columns 5 and 10.

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UDK/UDC	Ključne riječi	Key words
504.3.054 : 546.262	emisija ugljičnog dioksida po snazi i prevaljenom putu vozila	emission of carbon dioxide by vehicle power and elapsed mileage
311.1 : 629.113.	pokazatelj statističke snage motora i prevaljenog puta vozila	engine power and vechicle movement statistic indicator
504.3.054 : 665.73/.75	emisija iz motornih vozila zbog svojstava goriva	vehicle emissions due fuel properties
504.3.054 : 621.43.019	emisija iz motornih vozila zbog svojstava motora	vehicle emissions due engine properties
504.064.4	uvođenje tehnologiija smanjivanja zagađenja	introduction of wasteless and low waste technology
351.777 (4)	EU program za čišće motorno gorivo 1990-2009	EU programme for clean motor fuel 1990-2009 y.

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