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Car Window Filming, Tinting and Shading's Fuel, Emission Reduction and Economic Analysis around WA, NY, NC, USA and Istanbul, Turkey

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Abstract: Aimed Contribution—Fuel economy via car window film implementation will also reduce vehicle-sourced emissions, health and welfare impacts associated with those emissions; thus, contribute to the economy. Focused Problem—During summer, solar irradiation heats up the car and Mobile Air Conditioning (MAC) usage becomes essential. Moreover, MAC usage raises the fuel consumption and vehicle emissions. Eventually, imported energy sources for MAC and vehicle emissions lead global economic and health impacts. Proposed Solution—For a parked car under blazing sun in summer, car window film application limits the entrapped radiation in car cabin and reduces peak cabin temperature. Hence, MAC energy consumption will be reduced. Under consideration of film implementation costs, it is seen that MAC energy savings for diesel, gasoline and hybrid cars still contribute to the economy. Research Perspective—The physical and economic effects of several car window film and tinting applications are researched. Clear and tinted rear and side windows covered with three unique film types separately and analyzed for a parked passenger car with clear and 20 % shaded windshield. The overall impact in WA, NY, NC, USA and Istanbul, Turkey is also examined. Results—Regarding USA and Istanbul, the widespread deployment of the best possibility has potential to decrease the sum of diesel and gasoline fuel consumption by 1.7 and 0.06 billion liters, reduce the passenger car sourced total vehicle emissions by 10.5 and 0.4 billion kg and contribute to the economy by 5-year net savings of 21.3 and 1.4 billion $, respectively.

Keywords: Car window filming, car window tinting, car window shading, fuel, emission reduction, economic analysis, mobile air conditioning (MAC).

Nomenclature:

Acronyms	
EC	European Commission
FF	Film Free
GHG	Greenhouse Gas
GWP	Global Warming Potential
H_2ICE	Hydrogen Internal Combustion Engine
ICE	Internal Combustion Engine
MAC	Mobile Air Conditioning
NEDC	New European Drive Cycles
NREL	US National Renewable Energy Lab
P	Possibilities
R	Reference
S	20% Shaded
UV	Ultra Violet
UVA	Longwave Solar Radiation
UVB	Shortwave Solar Radiation
VLT	Visible Light Transmission
WHO	World Health Organization
wrt	with respect to
Chemical Compounds	
CFC	Chlorofluorocarbons
CH_4	Methane
CO	Carbon monoxide
CO_2	Carbon dioxide
HCFC	Hydrochlorofluorocarbons
HCHO	Formaldehyde
NMOG	Non-Methane Organic gases
NO_2	Nitrogen dioxide
NO_X	Nitrogen Oxides
PM	Particulate Matter
SO_2	Sulfur dioxide
VOC	Volatile Organic Carbon

Used in Calculations

ρ_{air}	Air density, kg m^{-3}
$A_{glazing}$	Glazing area, m^2
C	Saved cost, $
$G_{solar} = G_s = I_s$	Total solar irradiation on Earth surface, W m^{-2}
m_{air}	Cabin air mass, kg
$Q_{gain\text{-}1hr}$	Total heat gained after 1 hr-parking, W
$Q_{solar,\ gain}$	Heat gain by the surface, W
$\dot{q}_{solar,\ incident}$	Solar heat flux incident, W m^{-2}
SC	Shading Coefficient
SHGC	Solar Heat Gain Coefficient
T_{final}	Final car temperature, K
T_s	Surface temperature, K
T_{sky}	Effective sky temperature, K
V	Volume, lt
z	Saved MAC energy percentage (%)

Subscripts

D	Diesel
G	Gasoline
D+G	Diesel and Gasoline
D+G+P-F	Subscription of Filming Cost from Sum of Diesel, Gasoline and Prevented Pollution Savings

Greek Letters

α	Absorptivity
α_s	Surface Solar Absorptivity
ε	Emissivity

1. Introduction

Increased population, demand and requirement on mass production and transportation not only make harder to prevent emissions, but also result overpowering increase in global emissions. The air pollution treatment options are ought to consume additional energy and results more emission production unless the renewable energies are used and the sustainable development strategies are applied [1-2]. Against the conflict in its nature, treatment still serves as a solution while only the exhaust filters are applicable to vehicles to limit emissions. Moreover, even this narrow filtering option that leads more fuel consumption, which is inadequate to treat the exhaust gas that has many health impacts such as lung cancer [3].

Strategies like vehicle load reduction, improving energy efficiency, avoiding carbon-intensive fuel and techniques to reduce non-CO_2 GHGs from exhaust and MAC controls help to reduce GHGs linked to vehicle emissions [4]. Those strategies help to combat vehicle emissions as in European future proposed standards [5-6]. However, they are not enough to prevent or neutralize GHG emissions while the traffic and car sizes are increasing sharply.

MAC occupies a great portion in emissions due to fuel consumption. For USA, annual MAC fuel usage is 40 billion liters [7]. It is found that the windshield reduces fuel consumption by 3.4% [8], sunshade drops the soak temperature by 27% [9] and solar reflective car shells decrease MAC capacity by 13% [10]. Film application has the potential to decrease MAC energy loads of electric and other alternative energy using cars. Currently, nanotechnology product invisible films are available. Thus, invisibility may give an opportunity for film application to obey Visible Light Transmission (VLT) laws. In this study, conducted methodology has shown that the presented filming approach is a profitable as a quickly applicable alternative.

1.1 Background

(1) Emissions: Treatment can only separate the pollutant from the medium, yet cannot vanish the pollutant. Furthermore, throughout the treatment process this separation consumes energy and in some cases may end up producing more pollutant after separation from the medium. As a result, pollution reduction at the source has the highest waste hierarchy. Energy and fuel economy satisfies this criterion and owns very high importance. Transportation source owns 23% of world [4], 28% of U.S [11] total energy-related GHG emissions and 26% of Europe total energy-related CO_2 emissions [12] with 75% coming from road vehicles [4] and 30 to 50% coming from passenger cars [12]. Ideal Internal Combustion Engine (ICE) goal is to achieve complete combustion so CO_2 emission is a must. For USA and EU, the global fossil fuel CO_2 emissions are 4.4% and 2.9%, respectively. Throughout the vehicle life cycle, fuel combustion is responsible of 90% of the emitted

vehicle CO_2 emissions. Switching gasoline vehicle to diesel has potential to reduce CO_2 the emission to 24-33% in 2004 and 14-27% by 2050. Besides, vehicle operation produces CO, NO_x, Volatile Organic Carbon (VOC), Non-Methane Organic Gases (NMOG), Particulate Matter (PM), formaldehyde (HCHO), Hydrofluorocarbon (HFC), SO_x, small amounts of CH_4, N_2O and fluorinated gases from MAC [8, 12]. Emitted HFC-134a, CH_4, and N_2O from light duty vehicles have climate change impacts ~4%, 0.35%, and 2% of CO_2 emissions, correspondingly. Despite the recent development for filters like Diesel Particulate Filters (DPFs), they are insufficient. Relatedly, PM emissions coming from light duty vehicles were 0.9 billion kg in 2004 [12]. Hence, the vehicle emissions still need an attention. Black and organic carbon emitted from tail-pipe may affect radiative forcing [4]. Another emission source is evaporative emissions coming from evaporated fuel and refrigerant in heated car cabins [13]. Among them, annual emission range of the commonly used refrigerant fluid R134a (HFC-134a) is 0.75 to 2.5 million kg in Europe due to refrigerant leakages. Its peak range has Global Warming Potential (GWP) of 1300, equivalent to 3 billion kg of CO_2. 2011 European Commission (EC) regulation limits the refrigerant GWP by 150 for MACs [14].

(2) Emission's Effects on Health: Vehicle emissions are responsible for the increased health problems including cancer, cardiovascular, respiratory diseases and perinatal mortality [15]. World Health Organization (WHO) stated that diesel engine exhaust is carcinogenic to humans and its exposure increases lung cancer risk [3]. Among vehicle emissions PM and CO cause mortality and heart failure; PM, NO_x and SO_2 results respiratory illnesses such as asthma and bronchitis and increase the risk of an early angina. Examples of the other symptoms are change in immune system, lung inflammation, and respiratory symptoms of non-asthmatics [15].

(3) Emission Reduction Strategies: In order to reduce vehicle emissions, the possible options are listed as eco-driving, weight reduction, power reduction, energy efficiency improvement [4], strategies to reduce the MAC energy consumption [8], and switching the car type to a more efficient diesel [16], hybrid, electric technology, hydrogen internal combustion engine (H_2ICE) and hydrogen fuel cell vehicles. Although remaining actions are less effective, they include using low friction tiers and improved lubricants, and monitoring tire pressures to achieve stable and equal pressure as much as possible [12].

(4) MAC: Hot surrounding of a parked car may lead insufficient removal of the surplus heat via ventilation even at high flow rates, unless MAC is in use [17]. In California, more than 90% of the sold cars and small trucks have MAC [10]. For gasoline cars, MAC has the potential to increase fuel consumption by 35% and significantly higher for hybrids [18]. Even for high fuel-economy vehicles, MAC usage is enough to reduce the fuel-economy by ~50% whereas for mid-sized vehicles, by more than 20% while emitting more NO_x by 80% and CO by 70% [8, 12].

In order to combat against GHG emissions, EU designed to assess the low emission levels of car engines and fuel economy in passenger cars with New European Drive Cycles (NEDC) [19]. However, even NEDC does not encounter MAC related emissions [20]. EC regulation limits the maximum GWP of the MAC refrigerants by 150. Thus, the new technology focuses on increasing MAC efficiency while preventing any GHG and elimination of HFC. Possible alternatives of R134a are CO_2 and R152a. While GWP of CO_2 is only 1, the high-pressure operation of CO_2 requires costly and developed components and it brings risks at high ambient temperatures. For the second alternative, GWP of R152a is below 140, yet R152a is also a HFC and slightly flammable [14]. In a similar manner to combat against vehicle emissions, the U.S. Department of Energy's National Renewable Energy Laboratory (NREL) had started Cool Car Project in 2000. This project aims to reduce MAC fuel usage by 50% in the short-term and 75% in the long-term while ensuring

occupant thermal comfort and safety [8]. Rugh reported that 11.6 K of cabin air temperature drop increases fuel economy by 9.2% [21].

Energy saving for electric cars is also important for both energy saving benefits and the prevented air and heat pollution from power plants unless a renewable energy source is used. Electric car battery supplies the energy to an electric motor as well as other on-board accessories including lighting system, the audio system, and MAC. Among on-board accessories, the greatest power consumption belongs to MAC. The overall electric car engine efficiency shows that the commonly stated electric cars to be more efficient than gasoline and diesel cars need to be reviewed. Electric cars have the engine efficiency range of above 80% and on-board efficiency of 60% [22] while the maximum efficiency of ICE and turbines are 40%, and the diesel and gasoline car on-board efficiencies are around 20% [23]. For electric vehicle overall efficiency, the maximum electricity production efficiency of 40% in power plants [24], the additional small energy loss on the way of delivery and then 60% on-board efficiency of electric cars need to be considered. Resulted electric vehicle overall efficiency from source to move the car or to power accessories is maximum 25% and minimum 19% when the delivery losses are not taken into account. Surprisingly, this is very close to diesel and gasoline efficiencies of 20% [25]. Therefore, even the renewable energy sources are used to empower electric vehicles; reduction in MAC energy still plays another significant role for electric cars [26], as well as gasoline, diesel and hybrid cars. For passengers, the more the mileage per charge, the more the satisfaction and the more demand on electric cars. By considering 2.5 to 7.5% of total vehicle energy consumption belongs to MAC system [4], it is seen that minimization of MAC energy consumption is fundamental [7, 21, 26].

(5) Solar Irradiation and Protection Options: To begin with, greenhouse effect takes place when the solar rays are entrapped in vehicle through windows and heats up the car cabin [20]. In addition to convective heat transfer, the solar energy heats the vehicle by radiation especially across opaque components like the roof. All these heat sources raise the car cabin temperature, also called "soak" temperature. As a result of solar exposure and heat transfer, interior parts degrade, age [27-28] and ultimately have shorter life span. For the passengers [9] as well as the drivers, who may have driver fatigue in the end [26, 29], are subject to skin cancer [30].

The hot soak condition occurs when the parked car facing the equator is exposed to sun on a summer afternoon [31]. Ten minute-parking under blazing sun cause cabin and ambient temperature difference to reach 11 K [26]. Solar radiation is enough to increase dashboard temperature to 373 K (100°C) [17]. Experiments proved that when the solar load and the ambient temperature are 1000 W m^{-2} and 322 K (49°C), the direct sun exposure can raise the mid-size cabin and its surface temperature more than 355 K (82°C) and more than 394 K (121°C), respectively [8-9]. The greenhouse effect in car cabin is enough to raise the interior temperature above 60°C when the outside temperature is 27°C [20]. Hence MAC usage becomes obligatory but insufficient to protect the skin and the interiors from solar irradiation.

During hot soak conditions, the transmitted portion of the solar rays through the glazing accounts for 70% of the cabin heat gain [31]. The design of MAC capacity and size is based on maximum hot soak condition. This indicates that the reduction in the maximum hot soak condition via filming/tinting application will shrink MAC capacity and size, meaning that car weight and size will be reduced as well [21]. Tuchinda et al. describes the various glass types that can serve as a solution like insulating glass units [32]. Sullivan and Selkowitz, Farrington et al., and Hodder and Parsons researched solar reflective glazing while Al-Kayiem et al. studied the sunshade installation, and alternatively, Levinson et al. investigated the solar reflective car shells. All these

researches have shown listed sunshade cover visors types are capable of reducing soak temperature and cooling loads [8-10, 31, 33]. Sullivan and Selkowitz research goal was to achieve lower the release of ozone depleting MAC refrigerant of Chlorofluorocarbons (CFCs), which is phased out via Montreal Protocol like Hydrochlorofluorocarbons (HCFCs) and are being replaced with products such as HFCs, hydrocarbons, and CO_2 (EPA, n.d.). By advanced windshield usage, Farrington et al. achieved compressor reduction of 400 W and its equivalent fuel saving of 3.4% [8]. Al-Kayiem et al. suggested the installation of a sunshade that is capable to reduce the soak temperature by 27% [9]. Levinson et al. studied solar reflective car shells and simulated the decrease in soak temperature, reduction in MAC capacity, fuel savings and emission reductions. It is found that at occupant breath-level, air temperature dropped by 6 K and to cool the cabin down to 298 K (25°C) within 30 min, silver car has 13% less MAC capacity than the black car [10].

(6) Car Cabin Simulations: Currle simulates passenger car cabin temperature and airflow field [34], and Lin simulated them for the solar load [35]. Rugh performed CAD model of the passenger car, used DaimlerChrysler for meshing and Fluent as a solver, showed user-friendly vehicle solar load estimator written in MATLAB and capable of calculating the transmitted, absorbed, and reflective power of vehicle glazing, researched MAC load impact on the engine by using ADVISOR that can simulate ICE, series and parallel hybrid, electric vehicles, and compared the findings with the measurements [21]. Levinson et al. examined solar reflective car shells, calculated and simulated the decrease in soak temperature, reduction in MAC capacity, fuel savings, emission and MAC size reductions [10]. Jonsson studied the car compartment simulations by considering surface air speed [36]. Leong et al. conducted thermal simulations of an electric car cabin under static and ventilated conditions at different times of the day. The results are similar with Rugh, Al-Kayiem et al. and Quadri and Jose [9, 21, 26, 37].

(7) Passenger Comfort: Hot soak conditions or greenhouse effect in car cabin together with solar exposure affects many interiors including the vinyl materials of the dashboard, the leather covers and the electronic components. These conditions cause uncomfortable operating period for the passengers. In literature, this topic is identified as "vehicle cabin comfort" [9]. Hodder and Parsons found that the increase in the total solar radiation intensity plays more important role to affect thermal comfort than the specific radiation wavelength [33].

Currle studied passenger comfort based on passenger thermal model, the natural convection, the convective heat transfer and the radiation [34, 38]. Farrington et al. modeled thermal comfort for core and skin temperature, blood flow, sweating, and shivering as a function of time and correlated the findings with thermal sensation value and predicted percent satisfaction. Modeled parameters during time dependent heat balance are initial body temperature, body mass, clothing type and metabolic heat generation [8]. Taniguchi simulated the thermal comfort in car cabin and the passenger temperature sensation according to ASHRAE 2-node human skin model in different thermal conditions [39]. Rugh analyzed thermal comfort model on legs for hot and cold thermal receptors [21]. Chen et al. researched the same subject regarding occupant blood flow and human metabolism [18]. Rameshkumar et al. studied air temperature and velocity modeling surrounding passengers while running MAC [40]. In addition to occupant's discomfort and skin burns in case of a contact with heated cabin interiors [37], interior material ages as the cabin heats up. Muller and Vatahska's work focus on calculation and simulation of the aging of cabin interior components [28].

(8) Cabin Interior Damage: Sun exposure damages and ages cabin internal materials [28] like trims, plastic moldings, upholstery and seat covers. Especially, leather interiors are more prone to cracking and fading of surfaces. Al-Kayiem et al.'s suggestion of sunshade on windshield is found to reduce the

dashboard surface temperature by 26% [9].

(9) Heath Effects: The studies related with the deaths caused by the incidents in or around motor vehicles have shown that 34% of the fatality was caused due to leaving children alone and unattended in car cabins. Only for U.S., resulted hyperthermia ends up with annual child deaths of more than 30 [26]. It needs to be kept in mind that old and unconscious ill people are carries the same risk.

Driver fatigue is another important factor and defined as the decrease in concentration on the road and reflects that are responsible for fast and safe response to a potential danger while driving. Driver fatigue increases the risk of a crash since it is the reason for 30% of the road crashes [41]. Tsutsumi et al. have found that the car cabin environment affects driver's comfort, performance and fatigue [29]. Best and Shield stated that sun light causes more than 90% of skin cancers and the visible signs of skin aging [42]. Journal of the American Academy of Dermatology announced that 53% of skin cancers in the US occur on the left side while in Australia, drivers have skin cancer on the right [42], which may not be a coincidence with driver side. Furthermore, the skin cancer on the driver side can be caused by the UV (ultraviolet) exposure [30]. On a summer day, UV spectrum on earth's surface consists 3.5% of shortwave -UVB and 96.5% of longwave -UVA, which has adverse effects including immunosuppression, photo-aging, ocular damage, and skin cancer [32]. The window glass is capable of blocking UVB only while windshield partially filters UVA, and rear and side windows penetrate 63% of UVA [30]. Even if the rear window is made of dark glass, it can never provide enough UVA protection for the occupants sits at the back particularly babies and young children for having less protective skin pigment. It is reported that drivers in U.S. have more skin cancers on the left side of their faces, while drivers in Australia have on the right [42]. Primarily, driver head and neck and secondly, driver arm are mostly exposed to highest UV radiation. Moreover, 82% of the skin cancers on head and neck are on same sides [32]. The rougher, slacker and more wrinkled skin conditions occur on the window side of the long-term driver's body. Chronic UVA exposure may accelerate skin aging by 5 to 7 years [42]. Lastly, UV is potentially hazardous to eyes, intensely the cornea, lens and retina [32].

(10) Focused Solutions: When the car cabin is exposed to solar radiation, greenhouse effect takes place since the penetrated longwave radiation transforms into shortwave form that cannot pass through the glass and cannot leave the cabin. Sunshade cover visors protection mechanism starts after the solar radiation is entered through car windows. Therefore, sunshade cover visors can never achieve the same performance of the tinted glass and window films. These applications especially filming avoid a huge portion of the solar radiation to penetrate through windows, being trapped and accumulate in the car cabin [20]. As a result, the transparent window films that screens out almost 100% of UVB and UVA while providing clear visibility [30], and nanotechnology product invisible films, which are even invisible to an ordinary microscope [43] stand as a quickly applicable, cheap and effective solution.

According to Quadri and Jose, tinted glasses can also be used to protect skin, contribute to drive safer by preventing the driver from any glow of the roadside objects, preserve better comfort levels for providing cool car cabin, avoid constant use of MAC while driving, and contribute fuel economy and emission reduction [10, 37].

Presented research emphasizes the passenger car window filming effects around Washington (WA), New York (NY), North Carolina (NC) (to represent some of the significant states of US), U.S.A. and Istanbul, Turkey over the reduction of MAC fuel consumption, which prevents excessive vehicle emissions to be spread into atmosphere and eventually increase the economy by fuel savings, emission sourced cost savings [15], prolonging lifetime of the cabin interiors, and decreasing potential dangers on

human health and environment.

2. Materials and Methods

The methodology begins with assuming 1-hour of parking at noon in summer. The reference passenger car having only clear windows that is not tinted/filming or shaded, forms the first possibility of car scenarios. The focused passenger car scenarios are in two main groups with clear windshield and with 20% shaded windshield. Both groups analyzed for the possibilities having tinted rear and side windows only, and for three different types of film application either on clear or tinted rear and side windows. Explained car scenarios form 7 different possibilities including reference. Gained heat (Q_{gain}) of the reference car and 6 possibilities for clear and 20% shaded windshield separately calculated. Then, saved MAC energies are found from each application's Q_{gain} difference compared to the reference. After that, saved fuel, equivalent saved cost and prevented emissions are found for WA, NY, NC, USA and Istanbul, Turkey. Decreasing air pollution also has additional economic contribution [15]. It is assumed that films has 5-year guarantee and it is only paid once at the beginning of 5-year. Finally, net economic contribution is evaluated annually (1 summer) and at the end of 5-yr.

The minimum allowed shading only on windshield is taken as 20% as in USA VLT regulation [44] and as in previous studies [25, 45]. The total solar irradiations on the surface of Earth ($G_s = I_S$) are taken as 597 W m^{-2} for US, and 603 W m^{-2} for Istanbul. The reason for this assumption is that the average of hourly north-east/west and south-east/west orientations of total IS at noon varies according to latitudes of 20° to 60°N closely from 615 to 562 W m^{-2} [46], their average value is considered for all states in USA. Since Istanbul is close to 41°N, I_S value at 40°N [46] is used.

2.1 Description

First of all, film application energy, fuel, emission reductions and cost savings are estimated per diesel and gasoline car for U.S. and per gasoline car for Istanbul. The geographical impact is calculated from total number of passenger cars in traffic. The populations of WA, NY, NC and USA are gathered on Sep. 25, 2013 as 6,984,900; 19,570,261; 9,752,073; and 316,743,785, respectively. It is assumed that 80% [7] of the total 423 passenger cars (per 1000 people) in U.S. [47] are in traffic every day in summer. Its corresponding value for WA, NY, NC and USA is 2,363,690; 6,622,576; 3,300,101; and 107,186,097 [48]. On the other hand, for Istanbul, the total number of cars in traffic is published as 1.7-1.8 million and their average of 1.75 million is used [49].

Again from World Bank statistics, although the types of consumed fuel vary, the mainly used ones are diesel and gasoline in U.S. Hence, under the consideration of only diesel and gasoline is consumed in U.S. and by taking the ratio of diesel and gasoline, 26.3% and 73.7% [48] are used for diesel and gasoline, respectfully. However, since the diesel consumption in Istanbul is not as wide as US, calculations are conducted only over gasoline for Istanbul. The fuel prices per liter are taken as 1.04 $ for diesel and 0.96 $ for gasoline around U.S. [50] and 2.54 $ for gasoline for Istanbul [48].

It is considered as if all the cars possess MAC and use MAC to cool the car cabin every day in summer. Relatedly, overall energy efficiency through engine to MAC is conservatively chosen as 40% for diesel and 30% for gasoline. It is assumed that 80% of the passenger cars [7] are on-road everyday, park for 1-hr at noon in summer and then, use MAC to cool the soak temperature down to 298.15 K (25°C) [10, 51]. This quasi-steady comfort temperature of 298.15 K (25°C) is chosen for both initial and desired car cabin temperatures.

The average passenger car speed and performance are taken as 60 km h^{-1} [52] and 0.01 km m^{-3} [53], respectively. MAC system can draw 5-6 kW of peak power [54-55]. In general, its range is 0.4-3.7 kW due to temperature, oxygen concentration and engine speed [56], and it is used as 3 kW in calculations. The net

Coefficient of Performance (COP) of MAC is taken as 2 [7]. Medium sized car average interior volume index is used as 3.3 m^3 [25, 45, 57]. The car window dimensions of the windshield/rear windows and side windows are assumed as 1.4×0.5 m^2 and 0.55×0.4 m^2, respectively.

Unlike the previous study for Europe and EU [25], in this work, diesel and gasoline emissions are assumed the same throughout saved fuel emission analysis. Associated with emissions, smoke emission standard is considered the same with NMOG emission of 0.5 kg kWh^{-1} [25, 58]. Linked with complete combustion, CO_2 emission rate of ~0.58 kg km^{-1} is used [15].Gasoline engine passenger car emissions in kg pollutant per km of CO, NO_x, NMOG, PM, HCHO and VOC are used as 0.012×10^{-3}, 1.4×10^{-3}, 4.5×10^{-4}, 1.9×10^{-4} and 5.1×10^{-5} [59] and 4.9×10^{-4}, respectively. Finally, the cost of pollutants per kg of pollutant for CO_2, NO_x, VOC and $PM_{2.5+10}$ are 0.31 $ [15] , 8.1 $ [60], 2.4 $ [61] and 238 $ [60, 62], respectively. As a remark, emissions due to film production are not considered and film cost is taken as 40 $ per m^2 [63] and total cost is calculated over the total of all passenger cars in related geographic region, not 80%.

2.2 Selected Film Types, Tinted and Clear Windows

Developed film technology reflects the sunlight in summer and absorbs it during winter. To represent three unique groups, different film types are selected according to the best performance among their category. Film A blocks 97% of infrared heat and 99.9% of UV radiation; it is not metalized; and provides advanced clarity. Nano-tech Film B is selected for being invisible to naked eye and even to an ordinary microscope so that it would not violate VLT laws. Film B has low reflectivity, high clarity, heat reduction, tough properties and it is resistive to corroding. Finally, Film C is selected to symbolize old-fashion dark classic filming. Reference and filmed window possibilities and related properties are shown in Table 1 [43], where SC, SHGC, P, and R stand for shading and solar heat gain coefficient, possibilities, and reference, respectively.

Table 1 Properties of glass and film types.

P:	R	1	2	3	4	5	6	7
Glass:	Clear	Tinted		Clear			Tinted	
Film	-	-	A	B	C	A	B	C
SC	0.94	0.69	0.47	0.47	0.24	0.43	0.43	0.31
SHGC	0.82	0.60	0.41	0.41	0.21	0.37	0.38	0.27
α	0.88	0.5	0.39	0.36	0.09	0.23	0.21	0.05

2.3 Theoretic Calculations

Generally in literature, the mean radiant temperature approach is used to find Q_{gain} by car cabin as performed by Johnson and Rugh et al. [54-55]. Following previous works [25, 45], Cengel and Ghajar, and Cengel and Boles's procedures and the previously explained assumptions are applied to Stefan-Boltzmann law and Kirchhoff's law of radiation, where emissivity (ε) is confirmed to be equal to absorptivity (α) and taken as total transmitted percent. Procedure based on Kirchhoff's law of radiation (including Stefan-Boltzmann law) [51, 63] is:

$$\dot{Q}_{\text{solar, gain}} = \text{SHGC} \times A_{\text{glazing}} \times \dot{q}_{\text{solar, incident}} \quad (1)$$

$$\dot{q}_{\text{net solar, incident}} = \sum E_{absorbed} - \sum E_{emitted} = \alpha_s G_{solar} + \varepsilon\sigma\left(T_{sky}^4 - T_s^4\right) \quad (2)$$

$$Q_{gain,\ 1hr\text{-}park} = \dot{Q}_{gain,\ 1hr\text{-}park} \times 3600\text{sec} \quad (3)$$

$$Q_{gain,\ 1hr} = Q_{in\ car\ cabin} = \left(\rho_{air} V_{air}\right) c_p \left(T_{final} - 298.15\right) = m_{air} c_p \left(T_{final} - 298.15\right) \quad (4)$$

In Eq. (1), $A_{glazing}$ is the glazing area. 1.58 m^2 for rear and side windows and 0.7 m^2 for windshield are used separately for clear and for 20% shaded windshield. $\dot{q}_{\text{solar, incident}}$ is solar heat flux incident (W m^{-2}).

In Eq. (2), positive $\dot{q}_{\text{net solar, incident}}$ indicates heat gain by the surface and giving $\dot{Q}_{\text{solar, gain}}$ (W), which is the case. α_s is surface solar absorptivity, G_{solar} (G_s, I_s) is the total solar energy incident on surface, σ is the Stefan-Boltzmann constant of 5.67×10^{-8} W m^{-2} K^{-4}, T_{sky} and T_s are the effective sky temperature of 285 K for warm conditions and the surface temperature of 298.15 K at the beginning of the iteration, respectively [63]. In Eq. (3), $Q_{gain\text{-}1hr}$ is the total heat

gained after 1 hr of parking, m_{air} is the air mass in cabin (kg), obtained from air density ρ_{air} of 1.184 kg m^{-3} at 298.15 K [63] and V_{air} is the interior volume index of 3.3 m^3. It is further assumed that final car temperature T_{final} in car cabin will be equal to T_s. T_{final} is found after iterating the Eqs. (1)-(4) and the resulted peak error for clear car is ~10^{-6}. For the iterations, MATLAB loop is run for each possibility together with clear and 20% shaded windshield separately for USA and Istanbul.

3. Results and Discussion

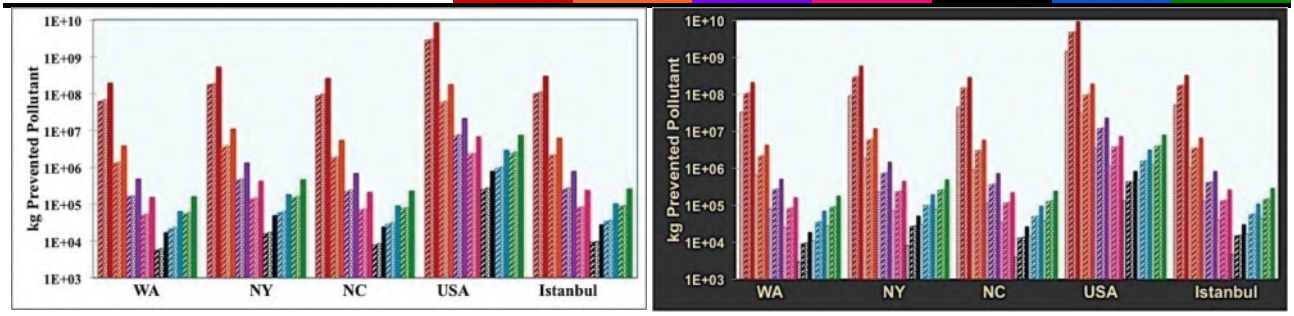
Evaluated results are listed in Table 2. The potential prevented vehicle emissions are shown in Tables 3-4 in detail. The annual and 5-year net savings for all possibilities are demonstrated in Table 5. In Tables 3-5,

Table 2 Energy and fuel savings, prevented total emissions, annual fuel and net savings, and 5-year savings for WA, NY, NC, USA and Istanbul, Turkey.

		Q_{D+G}		V_{D+G}		C_{D+G}		E_{Total}		C_{V+P-F}		$5C_{V+P-F}$	
		FF	S	FF	S	FF	S	FF	S	FF	S	FF	S
	P	10^{11} kW		10^8 lt		10^8 $		10^9 kg		10^8 $		10^8 $	
WA	1	0.1	0.2	0.1	0.1	0.06	0.09	0.0	0.1	-1.7	-1.6	-0.9	-0.4
	2	0.2	0.3	0.1	0.1	0.11	0.14	0.1	0.1	-1.5	-1.4	0.0	0.5
	3	0.2	0.3	0.1	0.2	0.12	0.15	0.1	0.1	-1.5	-1.4	0.1	0.7
	4	0.6	0.7	0.3	0.4	0.34	0.37	0.2	0.2	-0.7	-0.6	3.8	4.3
	5	0.3	0.4	0.2	0.2	0.18	0.21	0.1	0.1	-1.3	-1.2	1.1	1.7
	6	0.3	0.4	0.2	0.2	0.19	0.22	0.1	0.1	-1.2	-1.1	1.3	1.8
	7	0.6	0.7	0.4	0.4	0.36	0.39	0.2	0.2	-0.7	-0.6	4.1	4.7
NY	1	0.3	0.3	0.2	0.2	0.16	0.16	0.1	0.1	-4.7	-4.4	-2.6	-1.0
	2	0.6	0.6	0.3	0.3	0.31	0.31	0.2	0.2	-4.2	-3.9	-0.1	1.5
	3	0.6	0.6	0.3	0.3	0.33	0.33	0.2	0.3	-4.1	-3.8	0.3	1.9
	4	1.7	1.7	0.9	0.9	0.94	0.94	0.6	0.6	-2.1	-1.8	10.6	12.1
	5	0.9	0.9	0.5	0.5	0.50	0.50	0.3	0.4	-3.5	-3.2	3.2	4.8
	6	0.9	0.9	0.5	0.5	0.52	0.52	0.3	0.4	-3.5	-3.2	3.6	5.2
	7	1.8	1.8	1.0	1.0	1.00	1.00	0.6	0.6	-1.9	-1.6	11.6	13.2
NC	1	0.1	0.2	0.1	0.1	0.08	0.12	0.0	0.1	-2.3	-2.2	-1.3	-0.5
	2	0.3	0.4	0.2	0.2	0.15	0.20	0.1	0.1	-2.1	-1.9	0.0	0.7
	3	0.3	0.4	0.2	0.2	0.16	0.21	0.1	0.1	-2.1	-1.9	0.1	0.9
	4	0.8	0.9	0.5	0.5	0.47	0.51	0.3	0.3	-1.0	-0.9	5.3	6.0
	5	0.5	0.5	0.3	0.3	0.25	0.30	0.1	0.2	-1.8	-1.6	1.6	2.4
	6	0.5	0.6	0.3	0.3	0.26	0.31	0.2	0.2	-1.7	-1.6	1.8	2.6
	7	0.9	1.0	0.5	0.5	0.50	0.55	0.3	0.3	-0.9	-0.8	5.8	6.6
USA	1	4.5	7.3	2.5	4.0	2.52	4.03	1.5	2.4	-76.2	-71.1	-42.4	-16.9
	2	8.9	11.6	4.9	6.5	4.95	6.46	2.9	3.8	-68.0	-62.9	-1.5	24.0
	3	9.6	12.3	5.3	6.8	5.32	6.83	3.2	4.1	-66.8	-61.7	4.7	30.2
	4	27.4	30.1	15.2	16.7	15.20	16.72	9.0	9.9	-33.6	-28.5	170.9	196.3
	5	14.6	17.4	8.1	9.6	8.13	9.65	4.8	5.7	-57.3	-52.2	52.0	77.5
	6	15.3	18.0	8.5	10.0	8.48	10.00	5.0	5.9	-56.2	-51.1	57.9	83.4
	7	29.1	31.9	16.2	17.7	16.19	17.71	9.6	10.5	-30.3	-25.2	187.4	212.9
Ist, TR	1	0.2	0.3	0.1	0.1	0.09	0.14	0.1	0.1	-0.9	-0.7	0.8	2.1
	2	0.3	0.4	0.2	0.2	0.17	0.23	0.1	0.1	-0.5	-0.3	2.9	4.2
	3	0.3	0.4	0.2	0.2	0.19	0.24	0.1	0.1	-0.5	-0.2	3.2	4.6
	4	1.0	1.1	0.5	0.6	0.54	0.59	0.3	0.4	1.3	1.5	11.8	13.2
	5	0.5	0.6	0.3	0.3	0.29	0.34	0.2	0.2	0.0	0.3	5.7	7.0
	6	0.5	0.6	0.3	0.4	0.30	0.35	0.2	0.2	0.1	0.4	6.0	7.3
	7	1.0	1.1	0.6	0.6	0.57	0.63	0.3	0.4	1.4	1.7	12.7	14.0

Table 3 Potential emission reduction of CO_2, CO, NO_x, NMOG, HCHO, PM, VOC for clear windshield. Films applied on clear windows (a) and on tinted windows (b).

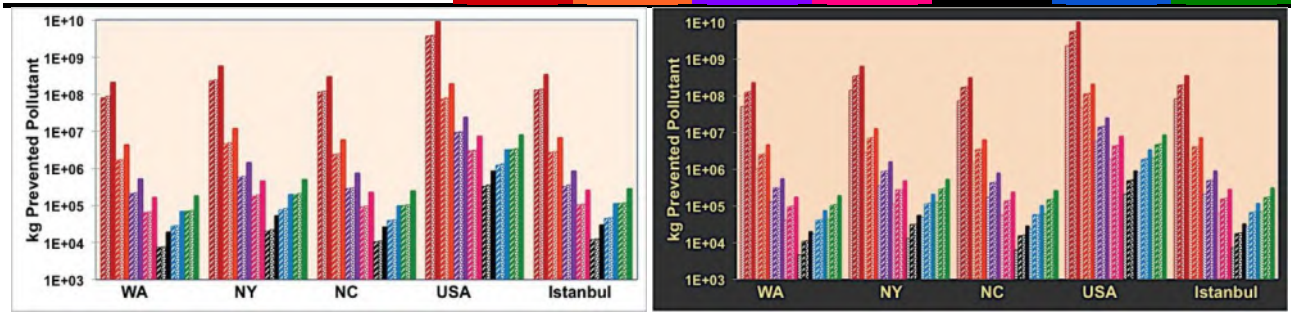
Graph matrix		CO_2	CO	NO_x	NMOG	HCHO	PM	VOC
Graph (a)	Graph (b)							
	Tinted only							
Film A	Tinted + Film A							
Film B	Tinted + Film A							
Film C	Tinted + Film A							



(a) **(b)**

Table 4 Potential emission reduction of CO_2, CO, NO_x, NMOG, HCHO, PM, VOC for 20% shaded windshield. Films applied on clear windows (a) and on tinted windows (b).

Graph matrix		CO_2	CO	NO_x	NMOG	HCHO	PM	VOC
Graph (a)	Graph (b)							
	Tinted only							
Film A	Tinted + Film A							
Film B	Tinted + Film A							
Film C	Tinted + Film A							



(a) **(b)**

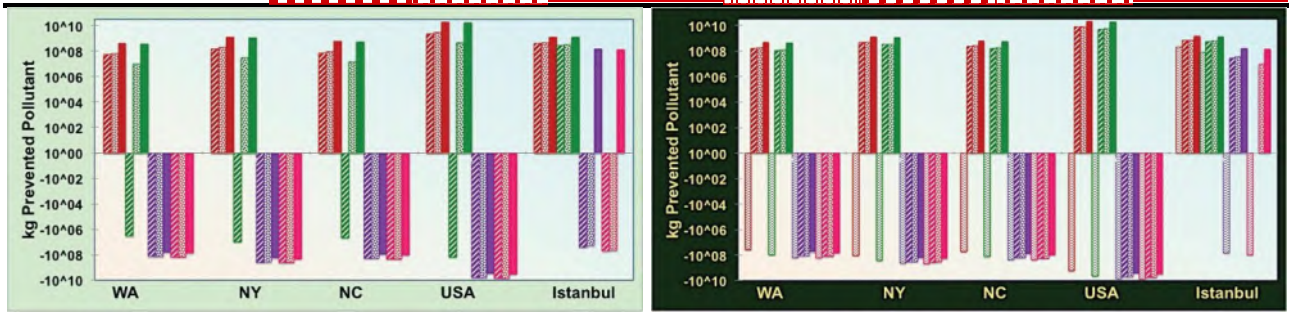
for graphs (a); Film A, B and C are always represented by following the first, second and third column sequence, respectively, and for graphs (b) only Tinted rear and side windows, Film A, B and C on tinted rear and side windows are always represented by following the first, second, third and fourth column sequence, respectively among each emission, annual and 5-year savings categories.

In Table 2, total saved MAC cooling energy belongs to diesel and gasoline engines (kW) is denoted by Q_{D+G}, saved diesel and gasoline fuel (lt) is V_{D+G}, total saved diesel and gasoline fuel cost in summer ($) C_{D+G}, the summation of all prevented emissions of CO_2, CO, NO_x, VOC, NMOG, PM and HCHO is E_{Total}. C_{V+P-F} and $5C_{V+P-F}$ are annual and 5-year net fuel and prevented emission cost savings remained after filming costs ($), respectively. *P*, *FF* and *S* (italic) stand for possibility, film free (clear) windshield and 20% shaded windshield, respectively.

In WA, NY, NC, U.S.A. and Istanbul, the total filming

Table 5 Potential emission reduction of CO_2, CO, NO_x, NMOG, HCHO, PM, VOC for 20% shaded windshield. Films applied on clear windows (a) and on tinted windows (b).

Graph matrix		Films applied on clear windows (a)				Films applied on tinted windows (b)		
Windshield	Savings	Film A	Film B	Film C	Tinted	Tinted + Film A	Tinted+ Film B	Tinted + Film C
Clear	Annual							
	5-year							
20% Shaded Windshield	Annual							
	5-year							



(a) **(b)**

cost is 0.19, 0.52, 0.26, 8.5 and 0.14 Billion $ over, respectively. The minus sign in front of $C_{D+G+P-F}$, indicates implementation cost overwhelms savings. While in USA every option seems unprofitable annually, In Istanbul, this is not the case. The reason behind it is that the gasoline price is 2.6 times of USA and the fuel calculations conducted only for gasoline since the diesel car usage is very low in Turkey. Hence, each saving results higher fuel economy. By considering the possibility of cost specific costumers, the ones in Turkey may have more tendencies to use filming or tinting when compared to USA. Still, the 5-year net savings may convince them.

The potential prevented vehicle emission graphs on logarithmic scale for a clear windshield are on Table 3 and for 20% shaded windshield are on Table 4. Table 3 shows the filming results applied on clear rear and side windows, while Table 4 shows tinted rear and side windows and filming on top of tinted rear and side windows. Film and tinting possibilities' annual and 5-year net savings in logarithmic scale for a clear and 20% shaded windshield are on both graphs on Table 5.

As seen in Table 2 and 5, except tinting only, each film application is profitable. In 5 years, even tinting becomes profitable in Turkey. On the other hand, film

Table 6 Q_{saved}/Q_{clear} percentages and duration of film cost to be neutralized.

	Q_{saved}/Q_{clear}		Film implementation cost recovery duration			
			Yr (summer)		Days (d)	
P	FF	S	FF	S	FF	S
1	7%	11%	10.01	6.25	901	562
2	14%	18%	5.09	3.90	458	351
3	15%	19%	4.74	3.69	426	332
4	42%	46%	1.66	1.51	149	136
5	22%	27%	3.10	2.61	279	235
6	23%	28%	2.97	2.52	267	227
7	45%	49%	1.56	1.42	140	128

implementation is shows important trend for fuel economy, decreased emissions and health benefits.

Tables 2-5 show that the Film C on tinted windows with 20% shaded windshield enhances the best performance. Performance can also be followed from percent MAC savings for film and window types in Table 6. Tables 2-6 clearly indicate that Film C owns the highest performance. Similarly, the lowest performance belongs to only tinted windows (7%) and among film types, it belongs to Film A and then, Film B on clear windows. However, for being invisible even to a microscope, due to VLT regulations, Film B can be preferred and still serves advantages especially in 5-year duration.

In order to see the impact, best performance outcomes in USA can be visualized as such: The total reduced CO_2, CO, NO_x, HCHO, PM and VOC emissions are 0.03% [64], 0.13%, 0.03%, 0.003%, 0.38% [12] and 0.016% [65] of respective global emissions. Specifically, the total reduced CO_2, HCHO and sum of all the GHGs emissions are 0.27%, 0.001%, and 0.13% of respectful emissions of EU. Moreover, total prevented CO_2 is 1% of EU CO_2 emissions coming from road [66]. The total saved power of the energy savings in 90 days of summer and 1-hr of each day is equal to 3 times of the average energy produced by nuclear power plant [67]. Nonetheless, the saved fuel road equivalent 17.7 billion km and one can travel 442 thousand rounds around equator of Earth [68]. This same MAC fuel savings is 17% of EU, 4% of U.S.A., and 0.55% of the world total annual fuel consumption by MAC [7, 55, 69]. Last but not least, the 5-year net saving can cover 0.047% of the current USA active passive budget difference of ~17.7 trillion $ [70].

Another important factor to follow filming, tinting and shading windshield is each possibility's saved MAC energy percentage to reference's consumed MAC energy (Q_{saved}/Q_{clear}).

$$z = \begin{pmatrix} -40.0715x^4+48.048x^3-15.699x^2+0.81445x \\ -31.8345y^4+424535y^3-18.7695y^2+3.48775y+0.0318 \end{pmatrix} \times 100 \quad (5)$$

$$\frac{Q_{saved}}{Q_{clean}} \times 100 = z \Rightarrow Q_{saved \text{ for Film N}} = z_{\text{for Film N}} \times \frac{Q_{clean}}{100} \quad (6)$$

Together with previous work [25], the new findings are evaluated and it is found that these percentages do not change among latitudes (Table 3). Hence, G_s does not affect Q_{saved}/Q_{clear}. However, to find the saved energy amounts, G_s must be used. So far, sensitivity analysis indicated that only two parameters affecting Q_{saved}/Q_{clear}. For a medium sized car with the given properties MAC energy saving percentage formula is driven via MATLAB and polynomial surface fitting in OriginPro software with R^2 of 0.985 and presented in Eq. (5). In Eq. (5), α, SHGC and saved MAC energy percentage (Q_{saved}/Q_{clear}, %) are denoted by x, y and z, respectively. Those two parameters affecting Q_{saved}/Q_{clear} are SHGC and α constants. In other words, not the saved energy amount, but the percentage depends only on film properties. As a result, customer can easily choose the film type by simply using Eq. (5). It is also easy to see that once the reference car cooling load is known, saved energy amount can be calculated. As seen in Eq. (6), instead of multiple iterations over Kirchhoff law of radiation, by just one iterative calculation for the reference car (Q_{clear}) and finding z in Eq. (5) would be enough to calculate any desired film application's MAC savings. Despite these benefits, it must be kept in mind that Eq. (5) thus, Eq. (6) would not give any idea about windshield shading effect.

All in all, each possibility has great potential to prevent significant amount of vehicle source emissions. As last a point, it is important to keep in mind that since CO, NMOG, and HCHO pollution cost data is missing, they are not considered in net savings.

3.1 Reference Car Modeling

Similar to Leong et al., simplified cabin geometry is used for the reference car [26]. The simple representative geometry is meshed with GAMBIT. Then, it is simulated in Fluent for the static radiation and convection heat transfer via 2nd order implicit unsteady transient solution from noon till 13:00 on 15th of July at 313.13 K (40°C) ambient temperature with solar tracking for 40°N, 30°E coordinates, when G_s is 603 W m^{-2} and cabin shell is aluminum. Fig. 1 shows static temperature distribution (K) in car cabin and Fig. 2 displays plotted temperature along the car width. The maximum and minimum temperatures are read from Fig. 2 as 345.5 K and 372 K and the average cabin temperature estimated as 358.75 K (85.60°C). It is seen that the simulation result is highly supported by the iteration result of 358.73 K (85.58°C). As a final check, Mezrhab and Bouzidi's thermo-electric model gives the similar results with final temperature of modeled cabin interior and the border [17].

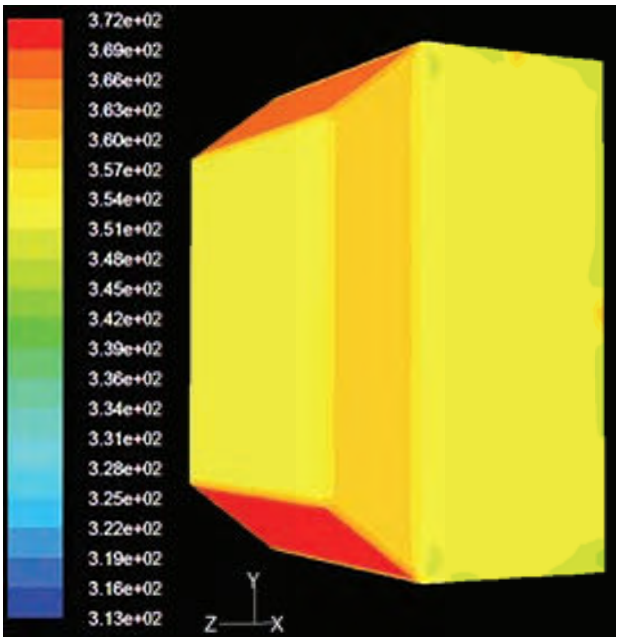


Fig. 1 Cabinstatic temperature distribution.

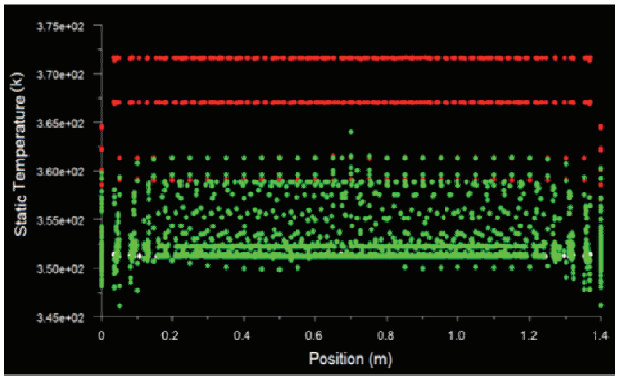


Fig. 2 Static temperature distribution plot along the car width.

3.2 Researchers Suggestions

During 12th CMAS Conference, Dr. Parakash Bhave and Dr. George E. Bowker have shared their related suggestions. Since this research focuses on the parking scenario under blazing sun, Dr. Bhave emphasized the importance of the coverage in open parking areas. Al-Kayiem et al.'s study on heating load effect of un-shaded parking areas supports this importance [9]. Dr. Bhave also suggested to model global evaporative and leaked refrigerant emissions, which reaches up to 3 billion kg of CO_2 equivalent in terms of GWP for Europe [14]. Dr. Bowker recommended new film technologies to perform as the photochromic lenses in eyeglasses so that it will darken when exposed to UV light and it will gradually became invisible as the light source disappears. Up until recently, the closest technology is known as electrochromic glazing. Electrochromic glazing needs low direct-current voltage to turn back to clear from tinted appearance. Additionally, other dynamic glazing technologies are under development and will soon be revealed [27].

4. Conclusions

In this research, three different film types on clear and tinted rear and side windows with clear and 20% shaded windshield effects on MAC energy savings, fuel economy, emission reduction and economic contribution are separately analyzed over WA, NY, NC, USA and Istanbul, TURKEY at noon in summer during 1 hour of parking. Theoretical iterative calculation result for reference passenger car is validated with simulation. It will be further researched for filming, tinting and windshield shading.

It is seen that saved MAC energy percentages (Q_{saved}/Q_{clear}) do not change for six total solar irradiation values and thus, Eq. (5) is driven to offer a quick approach without the need of any iteration. Eq. (5) is also ease the selection of film types for requiring two film parameters only. Eq. (6) enables to find any film's saved MAC energy amount just iterating once for the reference clear car. On future studies, Eq. (5) will be researched more to include different shadings, car interior volumes and the window size selection.

In conclusion, the scenario for Film C on tinted rear and side windows with 20% shaded windshield gives the best performance in terms of fuel economy, emission reduction and economic contribution. For USA and Istanbul, TURKEY, the best option serves the potential decrease in the sum of diesel and gasoline fuel consumption by 1.7 and 0.06 billion liters, reduce the passenger car sourced total vehicle emissions by 10.5 and 0.4 billion kg and contribute to the economy by 5-year net savings of 21.3 and 1.4 billion $, respectively. Even for costly or unprofitable

periods, film application would still protect passengers, block massive amounts of vehicle emissions and decrease the need for the imported fuel.

Additionally, for more accurate conclusion, energy consumption and emitted pollutants due to film production needs to be considered as well. The net cost savings are better to be calculated by considering the remaining air pollutants of CO, NMOG, and HCHO. It should also be noted that during driving, presented scenarios would bring further but less significant benefits including energy, cost, emission reduction, protection of health and increasing lifespan of the interior parts for preventing material aging, degradation.

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