Carpooling and the reduction of urban traffic

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Abstract. The article presents the results of research that quantitatively confirm the well-known thesis on the impact of carpooling (measured by the declared carpooling indicator, DCI) on a significant reduction in the intensity of urban traffic flows. Of course, it is about joint journeys by passenger cars, which (especially in medium-sized and large cities) are an important source of transport congestion, and the connection with the intensity of traffic is obvious. The working hypothesis was verified by conducting observations and measurements in the central area of a medium-sized city in Poland. It is the city of Radom, 100 km south of Warsaw, with a population of 215,000 residents. To verify the hypothesis, the average daily traffic volume, ADTV were compared with the average reduced average daily traffic volume, RADTV. These were determined - by simulating carpooling, in which the main control variable (although not the only one) was the indicator, DCI, i.e. the number of additional passengers in a passenger car. It turned out that RADTV values decreased significantly (therefore congestion decreased) when DCI values increased. This is illustrated by the DCI - RADTV dependence graphs for different days of the week and different measurement locations. This relationship was confirmed by calculating the Spearman's rank correlation index between the DCI and RADTV variables.

Keywords: carpooling, transport congestion, declared carpooling indicator /DCI/, reduced average daily traffic volume /RADTV

1. Introduction
About 90% commuting to work in France do it on their own. Increasing average occupancy rate of passenger cars by 12% from the existing value of 1.08 person would solve the majority of problems with traffic jams [1]. If these estimates are fine, then it shows what repair potential there is behind using of carpooling.

Transport congestion has been the problem known for ages. J. M. Thomson wrote that: „jams were the feature characteristic to London already long before inventing the car and in Rome – long before London was settled” [2]. But no earlier than in 20th century, in the period of intense development of automotive industry negative results of congestion became a big socio-economic problem. Congestion is a relatively long-lasting phenomenon when the level of traffic intensity of different means of transport is higher than the capacity of the infrastructure used. The effects of transport congestion significantly influence economic, environmental and social aspect of transport. It concerns mainly road transport, and most of all, transport in the cities. Among the most important disadvantages of transport congestion there are: time losses due to sitting in traffic jams, problems in finding parking places, degradation of the natural
environment (congestion is an important source of smog), impact on human health and life due to exposure to taking part in incidents and road collisions.

The concept that deserves particular attention is “carpooling”. It was created in the USA in the 1940s. Carpooling is currently experiencing great development in Europe, also in Poland, mainly due to the Internet network and social media. Carpooling can be described as a displacement system consisting in increasing the use of a passenger car, for example in city trips. The principle is simple and it assumes increasing the number of passengers while traveling by car. This is mainly done by matching commuters for work or study destinations on the same routes. The benefits are for both the driver and passengers traveling with them.

The impact of carpooling on the level of transport congestion is important. This issue has been studied many times, but few studies have explicitly concerned empirical verification of the basic research thesis in this area. And the thesis concerns the question: does increasing the carpooling coefficient really reduce the level of transport congestion in urban traffic? And what are the quantitative relationships here? Therefore, it would be a question of estimating the hypothetical correlation between "congestion level" and "carpooling coefficient". The authors attempted such a verification using the developed simulation model and the results of field traffic research in the city of Radom in Poland.

Congestion has been defined in various ways, see e.g. works [3], [4]. Congestion increases transportation costs considerably; it also generates other consequences - it has been written about these issues, among others, in the paper [5].

Many sources of transport congestion are known. They were shown, among others, in [6]. There are many methods known to reduce the level of transport congestion; here are some of them:

- increasing the capacity of roads and streets which is realized by expanding and modernizing of transport infrastructure [7], [8].
- implementation of methods of efficient use of the capacity of the existing transport system [9];
- managing transport demand [10],
- introducing changes in the spatial development system of cities and urban space management [11].

The positive effects of sharing means of transport are particularly visible in reducing congestion in medium-sized and large cities, especially where traffic participants use a passenger car together. There are many known vehicle sharing methods, including: carpooling [12 - 14]; carsharing [15-17]; ridesharing [18], [19].

The essence of carpooling has been described – among others - in the works [12], [20], [21]. Definitions and a review of the literature on carpooling systems are included, for example, in [22]. Factors that encourage the use of carpooling are described, inter alia, in [23].

A more recent review of the literature in this area, as well as in the field of carpooling studies, is presented in [24]. It is especially about:

- costs of commuting to work [25], [26],
- travel time savings and environmental awareness [26 - 28],
- travel mode selection [29], [30],
- access to potential carpoolers (people who are willing to join and travel with another person) [12], [31 - 36].

Other important factors influencing carpooling are: demographic factors (gender, race, education, profession), economic (household income, vehicle availability) and others. In particular, the general, economic and legal issues of carpooling as well as its relationship with congestion - have a rich bibliography. More recent works in this field include [8], [37], [38], [39]. Motivating factors for traveling together, also innovations and trends in mobility, also have extensive literature - just as an example we mention two interesting studies from UC Berkeley: Transportation Sustainability Research Center [40], [41].

It was also written about how Government and employers can support carpooling – for instance at work [42].

Also various methods and research techniques used in carpooling research are worth mentioning. Let us focus here on the study of carpooling behavior on the basis of online surveys [43], and simulation
modeling of carpooling [44]. On the other hand, theoretical and experimental aspects of "carpooling dynamics" are discussed for example, in [45].

The following works cover the impact of carpooling on the congestion level: [2 - 4], [6], [8], [46].

2. Materials and Methods

2.1. Research object and research concept.

The subject of the research were the streams of road traffic in the central area of Radom city, which is the city of medium size and which can be included in the group of “road cities”, namely these, where road congestion requires urgent reduction.

In 2018, the city of Radom had around 214,000 inhabitants, and 109,301 vehicles were registered here. The automotive index was 511 [vehicles / 1000 inhabitants] and it showed an upward trend. The city's street network was 291 km long, and the length of bicycle paths was 265; There were 496 taxis in the city. There were 265 road accidents that year with 13 fatalities and 322 injured.

The relatively large and still growing motorisation index heralds an increase in the transport congestion in Radom. In order to limit this phenomenon, it is necessary to introduce new forms of mobility - including planning some forms of carpooling.

Therefore, the main aim of the research (selected results of which are presented in this article) was the quantitative verification of the following working hypothesis: "increase in carpooling index means reduction of average daily traffic volume" (ADTV). And because the ADTV indicator indirectly shows the level of transport congestion - hence the reduction of ADTV, it is the reduction of transport congestion in urban traffic.

The verification of this research hypothesis has been carried out in the following stages:

1. ADTV measurements were made; in the area of the city where previously low levels of service traffic (LOS) were found, i.e. where congestion was particularly troublesome.

2. A model and a computer simulation program for carpooling was developed, where the main control variable of the simulation was the "declared carpooling indicator" (DCI) for passenger car journeys in Radom.

3. As a result of 100 simulations, the values of reduced average daily traffic volumes (RADTV), which indirectly characterize the level of transport congestion in the examined area of the city of Radom have been obtained.

4. ADTV results were compared with RADTV results calculated for different DCI values. These comparisons show that an increase in DCI implies a reduction in ADTV. Thus, the validity of the adopted working hypothesis has been demonstrated, which means that a quantitative correlation has been demonstrated between the increase in DCI and the reduction in ADTV, which indirectly describes the level of transport congestion in the analyzed measurement locations, ML.

5. The second (only preliminary) confirmation of the validity of the adopted working hypothesis was made - by calculating the Spearman's rank correlation index for the DCI and RADTV variables.

To sum up: the input data for the simulation program were the results of field traffic measurements in selected MLs of the city of Radom and the statistically compiled results of the questionnaire research on sharing places - only by people in passenger cars.

2.2. Levels' of service (LOS) analysis in the central area of Radom city

Field research / and survey research provided data on passenger car journeys in the city of Radom. There were three types of empirical data:

(1). Average daily traffic volume, ADTV - measured on the busiest sections of streets between selected intersections,

(2). Real (observed) fillings of passenger cars (FPC), in these measuring sections,

(3). Values of the declared (intentional) carpooling index (DCI).

ADTV and FPC values were measured in order to recreate the real urban traffic conditions in the simulation program. More precisely, the results of passenger car filling measurements were needed so that the simulation program could take into account the situations in which people from one vehicle
would fit into another vehicle going in the same direction. The measurement technique was simple: there were two people in the car, each of whom registered vehicles going in opposite directions of the analyzed inter-junction section.

Carpooling was simulated – with the change of DCI which is the number of people who want to take part in carpooling.

The map of measurements of ADTV and FPC parameters was developed using the known LOS values on the road and street network of the city of Radom. The most “jammed” sections between intersections (hubs), i.e. those where the highest ADTV values and the highest FPC values were previously recorded were selected for our own measurements. Traffic measurements in the city of Radom were carried out in the conditions of the highest daily traffic, i.e. from 7.00 - 10.00 a.m. and 2.00 - 5.00 p.m. The results of the LOS assessment concerned the so-called Radom Functional Area, [47], [48]. The LOS evaluations have been shown in Figure 1; individual LOSs are marked with colors: A - green; B - pink; C - yellow; D - orange; E - red; F - black.

Then, the LOS map was compared with the locations of traffic flow measurements in the city, which are carried out every year by the Municipal Road and Communication Authority in Radom. This comparison made it possible to select 20 measurement locations, in which own field research had to be carried out (in Fig. 2, black and white markers). It was in these locations that ADTV and FPC measurements were later carried out.

For particular test sites, the following was determined:
- traffic observer location points,
- measurement days: working day of the week, Saturday (before trading Sunday), Saturday (before Sunday without trading), trading Sunday, Sunday without trading,
- hourly range of measurements,
- measured values: ADTV, FPC.

2.3. ADTV measurements
Two-week measurements of traffic intensity were carried out on all previously established research sites (Fig. 2). This article presents some results of these traffic measurements. Figures 3 and 4 show the weekly measurement results for the test sites no. 18 (Wernera / Malczewskiego / Kelles-Krauza streets). The measurements were performed at 15-minute intervals.
The distributions of ADTV from Monday to Friday for both weeks are very similar and there is one peak of traffic, which indicates repeatability of traffic and therefore repeatability of vehicle filling. The traffic schedules for Saturdays and Sundays are different. In line with the assumptions of this work - the results of the measured ADTV from all 20 MLs were used in the computer simulation to determine the RADTV value.

2.4. Measurements of filling passenger cars in city trips
Measurements were carried out in 20 street cross-sections of the central area of Radom. The filling of cars was recorded for both traffic flows in a given cross-section of the street, in 15-minute intervals. The following values were measured and recorded:
- filling passenger cars, FPC;
- number of 2-person cars;
- number of child seats – occupied and free.
Exemplary results of car filling measurements (for working days of the week) are shown in the diagram (Fig. 5). From Monday to Thursday, between 7.00 a.m. and 10.00 a.m., the FPC index fluctuated in the range 1.14 - 1.54, with the weighted arithmetic mean 1.29 and between 2 p.m. and 5 p.m., the values were 1.22 - 1.67 and the average 1.4, respectively.

The following assumptions for creating carpooling simulation model have been developed:
- the 1st type driver, named "active" / "leading", can take passengers to his car,
- a type 2 driver named "passive" / "other" may become "active’s" passenger, if there is one,
- in the simulation there is an option to select the driver as "active" and "passive",
- simulation runs simultaneously for empirical data from all measurement sites; this means that at the start of the simulation cycle, the number of cars is summed up from all measurement locations and at the end of the simulation cycle it will be 'weighted' according to the ADTV value at each measurement location,
- with each simulation cycle, the probability of the passenger being picked up increases,
- a two-seater car cannot be equipped with a child seat,
- full cars can be “active” even though they can no longer take any passengers,
- the car will be refilled to five passenger seats.

Following the above (also other) assumptions, a carpooling simulation model was developed. This simulation allowed to assess the quantitative influence of the DCI control variable on the values of the RADTV index, which is the result of the simulation. The measured ADTV values and the observed FPC values were taken into account in the simulation.

The algorithm of the carpooling simulation program is as follows: Let NC denote the number of passenger cars observed in the 15-minute interval - located (in a given direction) on the in-between-hubs section. The carpooling simulation program performs the following operations:
1. selects from the pool of $N_C$ vehicles - the $f_S$ and $f_D$ fractions of demand and supply places in passenger cars,
2. determines the $f_S$ number of those cars where passengers want to join another vehicle,
3. determines the number $f_D$ of these cars in which passengers agree to take people from another vehicle,
4. each of the $N_C$ pool of cars has FPC values assigned,
5. each of the \( N_C \) pool of cars is assigned a fraction of \( p_E \), \( p_F \) of cars with empty and full seats. Therefore, in the simulation process, there are exchanges of "donors" and "recipients" of places in the analyzed \( N_C \) pool of passenger cars. These exchanges are registered at 15-minute intervals. Circulation (transfer) of people becomes a fact (an event in the simulation process) if it takes place in no longer than \( W_{T\text{max}} \) (the maximum waiting time for a joint ride). One vehicle is then subtracted from the \( N_C \) number of vehicles, and the procedure continues until all the vehicles that have left the original pool due to sharing are subtracted from the original \( N_C \) pool. Fraction of vehicles that remains gives RADTV when counted.

A more detailed description of the assumptions and the carpooling simulation mechanism will be presented in the prepared, much more extensive work.

The RADTV index, i.e. the simulation output value, can be written symbolically as a function of seven factors:

\[
RADTV = f\{N_c, f_s, f_p, FPC, p_E, p_F, W_{T\text{max}}\}
\]

(1)

If we describe the carpooling simulation model developed here in the black-box convention, the main input to the simulation is DCI, while the output is represented by RADTV, (Fig.6). It should be added that the simulation is controlled by changing the supply and demand values of the DCI index.

Carpooling simulation was written in C# language, project Windows Forms in the environment Visual Studio 2017 Community.

2.5. Data for simulation coming from questionnaire survey

In addition to the data obtained in traffic measurements in Radom, including the values of ADTV and FPC indexes, other data needed to perform a carpooling simulation was obtained in a questionnaire survey, on a random sample of 702 people. The aim of these studies was to obtain the empirical data needed to assess vehicle sharing preferences.

The respondents were residents of medium-sized cities in Poland (cities with 100,000-300,000 inhabitants). The questionnaire survey was not limited to the inhabitants of Radom, among other reasons, so that information could be gathered for a larger random sample. Moreover, the survey technique itself forced sending the questionnaires also outside the city of Radom.

The survey form contained only 8 questions. The first four questions concerned the respondent's demographic and social profile: gender, age, education, place of residence (here there were 5 categories
- ranging from rural areas to large cities). Question no. 5 concerned the professional status and the use of a private car as a work tool. Questions 6 and 7 concerned the SUPPLY of seats in the carpooling process. In question no. 6, the respondent answered whether he would like to participate in carpooling as a "donor" of a seat in the car, i.e. whether he would agree to take a person traveling in the same direction. In question no. 7, the respondent answered whether he would agree to be the "recipient", i.e. whether he would agree to get on another car going in the same direction, resigning from driving his own vehicle.

The declared total SUPPLY (answer - YES) of seats in the carpooling process was 60%, while the answer NO (32%). 8% of the respondents did not drive a car.

It turns out that 52% of respondents would not give up driving their own car. So 48% - it is the declared total DEMAND for “giving someone a lift”, that is, the declared DEMAND in the hypothetical carpooling in Radom.

Question no. 8 also indirectly characterized the DEMAND for places in the carpooling process. The potential "recipient" of the place in the car answered the question: How many minutes maximum could you wait for another car that would go in the same direction and get on it, giving up driving your own car? The histogram of the WT\textsubscript{max} value is shown in Figure 7.

![WT\textsubscript{max} histogram](image)

The weighted arithmetic mean of the WT\textsubscript{max} index is 4.08 minutes, which means that the statistical “demand” respondent was quite “impatient”.

The shape of the above histogram is interesting. About 70% of the survey respondents (the first three bars of the histogram) declare slightly more than 30% of the WT\textsubscript{max} value (1.5 - 4.5 minutes). Thus, the WT\textsubscript{max} histogram resembles the Pareto diagram with the 70/30% rule, which is slightly weaker than the original Pareto observation (80/20%). Here, the proportion of 70/30% means that over 2/3 of the population of potential (declaring) carpoolers in a medium-sized Polish city is interested in the shortest "thirty percent" of the maximum time available to them to wait for a place in the carpooling system.

### 3. Results and discussion

The input data for the simulation was prepared and introduced on the basis of field tests and measurements. The percentage of "recipients" and "donors" was the same in the studies. The simulations were carried out consecutively for the following fractions: 10, 20, 30, 40, 50, 60, 70, 80, 90, 100% of people, where the fractions of "recipients" and donors of carpooling seats were the same, which is a simplification at this stage of the simulation. Carpooling was simulated on: weekdays, Saturdays before trading Sunday, Saturday before Sunday without trading, trading Sundays and Sundays without trading.
Each of the simulated time periods was divided (it was to comply with field tests) into 15-minute intervals.

3.1. Illustration of DCI – RADTV dependence

The simulation confirmed the verified working hypothesis: an increase in carpooling (increase in DCI) significantly reduces the intensity of road traffic (RADTV).

Figure 8 show exemplary simulation results - these are graphs showing the dependence of RADTV on the changing (every 10%) index controlling the DCI simulation.

![Figure 8. RADTV simulation](image)

3.2. Spearman’s rank correlation estimator in the study of dependences between DCI and RADTV indexes

The dependence between the DCI which controls the carpooling simulation and the RADTV which is the result of the simulation can also be confirmed differently and simply (see Figs. 11-26). It is enough to calculate the Spearman’s rank correlation coefficient for these variables; it must be assumed that both variables can be treated as step random variables - although they are not. Both these variables are described by sequences of numbers determined for 15-minute intervals in the measurement (and simulations) interval, i.e. in the time interval [7.00 a.m. - 6.45 p.m.]. The RADTV variable is specified by the sequence of simulation result values. But, the values of the DCI variable are also non-random DCIk values of this variable (expressed in%), which control the carpooling simulation. Yet, each of these numerical values can be formally written as the value of a one-point probability distribution with the distribution function

\[ pk = Pr(DCI = DCIk) = 1, \text{ for } k = 1, 2, ..., 11. \]

Thus, the sequence of DCIk values controlling the carpooling simulation can be interpreted as a sequence of independent random variables with single point distribution. This sequence consists of \( n = 11 \) elements, where \( n \) - the number of carpooling "levels of control" - into which the DCI variable is divided, (\( DCI = 0, 10, 20, ..., 100 [\%] \)). Similarly, the sequence of RADTVk result values can be formalized - as a sequence of independent one-point random variables, where each of these values is assumed with a probability of 1.

When comparing the carpooling simulation results, it can be seen that increasing DCI causes a reduction in RADTV for all test time intervals and at all measurement locations. Then the maximum rank mismatch occurs. The Spearman’s rank correlation coefficient \( rs \) (DCI, RADTV) of the DCI and
RADTV variables is calculated for \( n = 11 \) values obtained as a result of carpooling simulation (data to be calculated in the table below).

4. Conclusion
Creating new mobility in cities should ensure the possibility of using various methods of transfer realization in the transport space. It is also worthwhile to pay attention to various systems that allow for transport dedicated to people who prefer to use a passenger car for these purposes. Various activities can be undertaken on this occasion to encourage car sharing. This is particularly important, because, as indicated by numerous publicly available literature sources in the European Union, as many as 41% of people make their journeys with the use of a passenger car. If it is not possible to change habits regarding everyday movements, then travelers should at least be encouraged to use more car space.

The average filling of passenger cars varies depending on the place, day, time and direction of the traffic flow, though, the filling of all vehicles mainly consists of one or two people. The vast majority of cars on Radom, but also on Polish roads, can accommodate four or five people. Filling the vacancies with passengers from other cars will reduce the total number of vehicles in motion, which was confirmed by the simulation results. Roads will become less congested and travel times will be significantly shorter.

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