CITY OF
WEST CHICAGO

WHERE HISTORY & PROGRESS MEET

Plan Commission/Zoning Board of Appeals
Tuesday, December 6, 2022
7:00 p.m.

West Chicago City Hall
Council Chambers
475 Main Street
West Chicago, IL 60185

AGENDA

1. **Call to Order, Roll Call and Determination of a Quorum**

2. **Pledge of Allegiance**

3. **Chairman's Comments**

4. **Public Comment**

5. **Approval of the Draft November 1, 2022 Meeting Minutes**

6. **Public Hearing of Case PC 22-07 *(To Be Continued to January 3, 2023)***

   QuikTrip Corporation has requested that the Plan Commission/Zoning Board of Appeals continue the public hearing for their case to the Tuesday, January 3, 2023 Plan Commission/Zoning Board of Appeals meeting.

7. **Approval of 2023 Meeting Dates**

8. **Petition Updates/Status**

9. **Next Meeting –** Tuesday, January 3, 2023 at 7:00 p.m.

10. **Adjournment**

cc:		
	Plan Commission Members	School Districts #25, #33, #94, #303, #46
	Mayor	West Chicago Fire Protection District
	City Council	West Chicago Park District
	M. Guttman	West Chicago Public Library District
	T. Dabareiner	DuPage County Building & Zoning
	M. Patel	Warrenville Plan Commission
	J. Sterrett	News Media

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Ruben Pineda
MAYOR

Nancy M. Smith
CITY CLERK

Michael L. Guttman
CITY ADMINISTRATOR

Draft
PLAN COMMISSION/ZONING BOARD OF APPEALS
November 1, 2022 7:00 P.M.

1. Call to Order, Roll Call and Establishment of a Quorum
Chairperson Laimins called the meeting to order at 7:00 p.m. Roll call found Chairperson Laimins and Commissioners Banasiak, Billingsley, Hale, Henkin, and Slattery present. Commissioner Kasprak was absent. With six members present, a quorum was established.

Staff in attendance was City Planner John Sterrett.

2. Pledge of Allegiance – Chairperson Laimins led the Commission in the Pledge of Allegiance.

3. Chairman's Comments – Chairperson Laimins explained the Rules of Procedure for the public hearing on the agenda.

4. Public Comment – None.

5. Approval of the Draft Minutes of the October 4, 2022 Plan Commission Meeting
Commissioner Hale made a motion, seconded by Commissioner Billingsley, to approve the October 4, 2022 Plan Commission meeting minutes. With a voice vote of four "ayes", zero "noes", and two abstentions, the motion carried and the draft minutes of the October 4, 2022 meeting were approved.

6. Public Hearing of Case PC 22-07 – Preliminary Planned Unit Development and Plat and Special Use Permit
Commissioner Banasiak made a motion, seconded by Commissioner Henkin, to reopen the public hearing for Case PC 22-07 for a Preliminary Planned Unit Development and Plat and Special Use Permit for QuikTrip Corporation at the southeast corner of Illinois Route 59 and Illinois Route 64. With a voice vote of all "ayes" and zero "noes", the motion carried and the Plan Commission reopened the public hearing for Case PC 22-07.

Mr. Sterrett was duly sworn in. Mr. Sterrett stated that QuikTrip Corporation is petitioning the City for approval of a Preliminary Planned Unit Development, Preliminary Plat of Subdivision, and Special Use Permit to allow the development of a vacant 24.25-acre property, owned by QuikTrip Corporation. The property is located on the south side of Illinois Route 64 and on the east side of Illinois Route 59, located in the B-3 Regional Shopping District. The property is surrounded by established commercial uses on the north, west, and northwest side including the Mosaic Shopping Center to the north, St. Andrew's Shopping Center to the west, and the Franciscan Plaza Shopping Center kitty-corner. Additionally, Shell Gas Station is located immediately to the northwest at the hard corner of Illinois Route 64 and Illinois Route 59. The Waynewood residential subdivision in unincorporated DuPage County is located immediately to the east and the City owns vacant property immediately to the south, which contains a detention area that serves the Prestonfield residential development.

Mr. Sterrett stated that the proposed project consists of a phased commercial development containing four commercial lots. The petitioner is proposing three access points for the development: A full access with a traffic signal at the far south end of the property on Illinois Route

59 that will line up with Heritage Woods Drive, a right-in/right-out access on Illinois Route 59 approximately 940 feet north of the proposed full access drive, and a three-quarter access on Illinois Route 64 across from the existing middle access point of Mosaic Crossing shopping Center, near the new Kid's Empire and Planet Fitness. Both Illinois Route 59 and Illinois Route 64 are state arterial roadways and under the jurisdiction of the Illinois Department of Transportation. The location and type of these access points are dictated entirely by IDOT and have been approved by the agency as shown. The site will also contain a stormwater detention facility on the east side of the development. The facility is not designed to hold standing water. Instead, the detention area will fill with rain water during a storm and slowly be released to the property to the south, which is owned by the City, at the same rate that the subject property currently conveys stormwater onto the City-owned property. The proposed stormwater detention area has been preliminarily approved by the City's stormwater engineer and complies with the DuPage County Stormwater Ordinance. The proposed utility layout and preliminary engineering have received preliminary approval from the City's Public Works Department and stormwater engineer.

Mr. Sterrett stated that in addition to the Preliminary PUD and Plat, the petitioner is requesting approval of a special use permit on the new Lot 1 for a motor vehicle service station, also known as a gas station. The use will consist of a 8,292 square foot convenience store to be open 24/7 known as QuikTrip and will have a canopy for regular pumps along Illinois Route 64 and a canopy for diesel trucks located in the rear of the building. A truck scale is also proposed near the diesel canopy. The convenience store will be constructed in accordance with the City's design standards and the petitioner will install landscaping on Lot 1 in compliance with the City's landscape ordinance. Proposed building and freestanding signage will comply with the City's Sign Code and all exterior lighting will comply as well including having light levels drop to 0 foot-candles before light reaches the property lines and providing shielding of lights to prevent glare.

Mr. Sterrett stated that the property is designated as Corridor Commercial within the Comprehensive Plan that the City approved earlier this year. This designation as commercial for future use of the property has existed as far back as 1975. Both a commercial Planned Unit Development and a Motor Vehicle Service Station, are identified in the City's Zoning Code as Special Uses. Staff has drafted findings of fact, contained in the staff report, and posted publicly on the City's website, and recommends the Plan Commission adopt these findings with their recommendation. Mr. Sterrett stated that staff recommends that the Plan Commission pass a motion recommending to the City Council approval of the requests. Several conditions are recommended to be added to this recommendation to mitigate potential impacts from the development on surrounding properties, including:

1. That the site be developed in substantial conformance with the plans submitted for consideration
2. That the proposed shade trees immediately east of the truck parking stalls shall be replaced with eight foot tall evergreen trees. These trees shall be included on the Final Landscape Plans.
3. That the Final Landscape Plans include a greater variety of shrubs throughout the site, both along property lines and foundation landscaping.
4. That overnight truck parking be prohibited on Lot 1 and the petitioner shall install signage at the truck parking stalls indicating this prohibition.
5. That the columns for the gas pump and diesel pump canopies be wrapped in either brick or stone to match the architecture of the convenience store building.

Mr. Sterrett stated these conditions have been shared and are acceptable to the petitioner. Mr. Sterrett also stated that if during the course of the public hearing the Plan Commission determines that additional conditions may be necessary to adequately mitigate any potential impact from the proposal, the Plan Commission may recommend those as well.

Erik Eckhart, representing QuikTrip Corporation was duly sworn in. Mr. Eckhart provided a background to QuikTrip and went over in additional detail the site plan and the proposed operation of the site and proposed use.

The following members of the public were duly sworn in by the court reporter and spoke in opposition to the proposal:

Fred Turner of 29W681 Waynewood Drive raised concerns regarding gas fumes from trucks and contamination of water runoff.

Tom Butkovich of 29W651 Waynewood Drive raised concerns about fumes going to the senior centers to the west of the property, gasoline spills, and truck traffic.

Susan Corriero of 29W651Waynewood Drive raised concerns about overnight truck parking, diesel air pollution, truck noise pollution, and the meeting notification requirements.

Dan Sonsedek of 2N610 Valewood Road raised concerns about contaminated water runoff, light pollution, and traffic.

Jeff Seick of 29W721 North Avenue raised concerns about gasoline fumes and traffic.

George Mack of 2N665 Valewood raised concerns about well water contamination from diesel gas runoff and where revenue from the proposed gas station would be going.

Neil Puccetti of 29 Valewood Drive raised concerns about water runoff and traffic.

Laurie Norris of 2N560 Valewood Drive raised concerns about the notification requirements and impact on property values.

Bob Norris of 2N560 Valewood Road raised concerns about the trucks, potential crime, and traffic.

Dan Budziak of 2N645 Valewood Road raised concerns about property values and impacts to well water.

Brad Burlage of 2N632 Valewood Road raised concerns about soil contamination and traffic.

Tim Green of 2N515 Woodcrest Drive raised concerns about well water, diesel spills, traffic, and flooding.

Catherine Edman of 0N766 Woods Avenue, Wheaton, raised concerns about traffic, the difference in elevation of the property and the homes to the east, fencing, stormwater, sales tax revenue, and funding for the proposed traffic light.

Mr. Eckhart provided information and answered questions on underground fuel tanks to prevent leaks, information on security monitoring, and 24-hour maintenance including fuel spills.

Jonathan Smith of 208 South Church Street, Wauconda, engineer for the petitioner, provided information on the oil/water separator system to prevent fuel spills from running off the site.

Robert Codden of 29W535 Hawthorne raised concerns about air contamination from diesel fumes.

Tim Green of 2N515 Woodcrest Drive raised concerns about diesel fuel spills on the ground and how soil contamination will be prevented.

Mr. Smith stated that all IEPA regulations and permitting must still be sought that will address this.

Jeanne Niedra of 2N538 Valewood Road raised concerns about contaminated water runoff affecting well water.

Fred Turner of 29W681 Waynewood Drive asked questions regarding the treatment train for oil/water separation. Mr. Smith responded to these questions.

Alfred Cedeno of 29W606 Waynewood raised concerns on the overall value and effects on the neighborhood including wells, and traffic.

Skip Kramer of 29W601 Waynewood Drive raised concerns about diesel truck fumes, water contamination, traffic, and spills from diesel fuel.

Mr. Sterrett explained that the property has been zoned commercial since at least the 1970s, and that commercial zoning included gas stations as a special use permit.

Sharon Nolan of 29W520 Glen Road raised concerns regarding property values affected by the proposal and water contamination.

Carol Townsend of 1364 Sweet Bay Lane raised concerns regarding trucks stopping at the proposed stop light and property values.

Teresa Camino of 2N735 Woodcrest Drive raised concerns regarding water retention and that the public hearing sign was only written in English.

Christina Jakubas of 2N351 Glen raised concerns about the health and safety of the residents.

Mr. Sterrett explained how and what City staff reviews in regards to a Planned Unit Development and Special Use Permit, which includes verifying that the proposal meets City Codes. The City does not have jurisdiction to enforce County, State, or Federal laws, as those are regulated and enforced by the appropriate County, State, or Federal agency.

Katrina Hish of 16 Waynewood Drive raised concerns about contamination of the land, increase in crime such as drugs and human trafficking.

Mr. Green raised concerns about notification requirements from the petitioner. Mr. Sterrett addressed the notification requirements. Mr. Sterrett also explained what a special use permit is.

Juan Galvan of 29W735 Valewood Road raised concerns about destroying the ecosystem of the subject property, regeneration of semi-trucks, noise, crime, and pollution.

Ms. Niedra raised concerns regarding the Findings of Fact contained in the staff report.

Mr. Eckhart stated that they will have a finalized grading plan once the final engineering plan is put together. Mr. Eckhart answered questions from the Plan Commission and discussed a portion of their annual profits going back to the community and stated fencing and maintenance of the green area on the east part of the property will be included in the final plans. Mr. Eckhart also answered questions regarding idling trucks and they must look into this matter.

Nick Ftikas of 221 North LaSalle Street, Chicago was duly sworn in. Mr. Ftikas is the attorney representing the petitioner and reiterated that this a preliminary approval and that they will be back for final approval. All IEPA permits must still be sought. Mr. Ftikas answered questions from the Commission regarding the cleaning of the treatment train.

Mr. Sterrett answered questions from the Commission regarding the stormwater detention and that the amount of detention needed is based on net new impervious surface. Mr. Sterrett also answered questions related to the concern on the internal drive and potential cut-through traffic. Mr. Sterrett explained that the internal private drive is required to be maintained by the required owners' association. Mr. Sterrett also answered questions related to the sidewalks being proposed along the development.

Mr. Eckhart answered questions from the Commission regarding the proposed truck scale. Mr. Sterrett answered questions from the Commission regarding notification and sign posting requirements. Mr. Ftikas clarified how the required mailing was sent and how the names and addresses of those within 250 feet was obtained by the Wayne Township Assessor.

The Plan Commission began to review the draft Findings of Fact and had concerns regarding potential environmental impacts, impact on surrounding properties, and impact on property value. Mr. Ftikas stated that Quiktrip will perform a full air-quality impact study and an environmental impact study to bring back for review by the Plan Commission.

Commissioner Billingsley made a motion, seconded by Commissioner Henkin, to continue the public hearing to December 6, 2022. A roll call vote found Commissioners Billingsley, Banasiak, Henkin, Hale, Slattery, and Chairperson Laimins voting aye. With a roll call vote of six ayes and zero noes, the motion carried and the public hearing was continued to December 6, 2022.

7. Adjournment

With no further business to discuss, Commissioner Billingsley made a motion, seconded by Commissioner Henkin to adjourn the meeting. With a voice vote of all ayes, the motion carried and the Plan Commission, at 10:37 p.m., adjourned.

Respectfully Submitted,
John Sterrett, City Planner

DEPARTMENT OF
COMMUNITY DEVELOPMENT

TOM DABAREINER, AICP
DIRECTOR

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MEMORANDUM

TO: Plan Commission/Zoning Board of Appeals

FROM: John Sterrett, City Planner

DATE: December 1, 2022

RE: PC 22-07 – QuikTrip Corporation – Move to Open and Continue the Public Hearing to January 3, 2023

The public hearing for Case PC 22-07 – QuikTrip Corporation, opened on Tuesday, October 4, 2022 and at the request of QuikTrip was immediately continued to the Tuesday, November 1, 2022 Plan Commission/Zoning Board of Appeals meeting. No discussion occurred at the October 4th meeting. At the continued hearing on November 1st, QuikTrip presented their requests and public comments were provided. The Commission continued the hearing to Tuesday, December 6, 2022 pending the completion and review of two environmental studies that QuikTrip offered to perform.

QuikTrip has requested that the hearing be continued to Tuesday, January 3, 2023 to complete these studies. The Commission should move to reopen the hearing at the December 6th meeting and then move to continue the hearing to the January 3rd meeting.

Additional public comment has been received by staff since the November 1st meeting and is included in the December 6th meeting packet. This information has also been sent to the petitioner.

###

John sterrett

From: Dan Sonsedek < >
Sent: Monday, November 28, 2022 2:41 PM
To: John sterrett
Subject: Re: PUD 22-07
Attachments: IL West Chicago QuikTrip Potential Impacts Letter 11-17-2022 (3).pdf

John,
Hope you had a great weekend and Thanksgiving. I have been working with a Community and Environmental Defense service to gather supporting facts and studies to show support to our community's request to not build the truck stop. The findings are attached below. I ask that the members please take the time to read through this. As it cost us as a community a great deal of time and money. I will be sending over more supporting facts this week to be sure we are ready for the December 6th meeting and hopefully a vote to end this. Feel free to contact me if you have any questions.
Thanks Dan Sonsedek

--

COMMUNITY & ENVIRONMENTAL DEFENSE SERVICES

Richard D. Klein
24 Greenshire Lane
Owings Mills, Maryland 21117

410-654-3021
Help@ceds.org
ceds.org

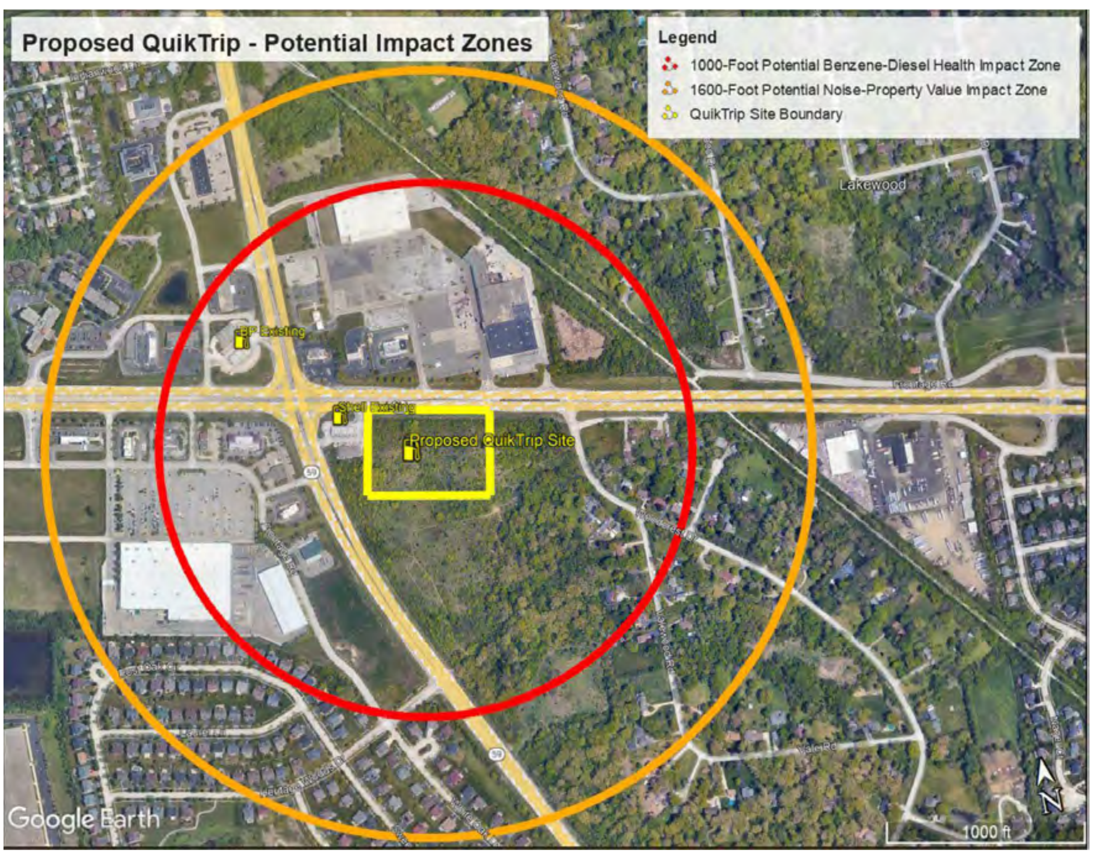
November 17, 2022

Dan Sonsedek
2N610 Valewood Road
West Chicago, Illinois 60185-1727

RE: Potential Neighborhood Impacts - Proposed QuikTrip Travel Center (PC 22-07)

Dear Mr. Sonsedek:

As requested by you and your hundred plus concerned neighbors, I have reviewed the proposed QuikTrip Travel Center, which would consist of a gas station, truck stop, truck scale, and a convenience store. The project is proposed for the South side of Illinois Route 64 (North Avenue), East side of Illinois Route 59 (Neltnor Boulevard), in West Chicago, Illinois. The applicant, QuikTrip Corporation, has requested approval of the project as a Planned Unit Development (PUD) and a Special Use Permit for a Motor Vehicle Service Station. As shown in the aerial below, numerous homes are within the 1,000- to 1600-foot potential impact zones documented in this letter.

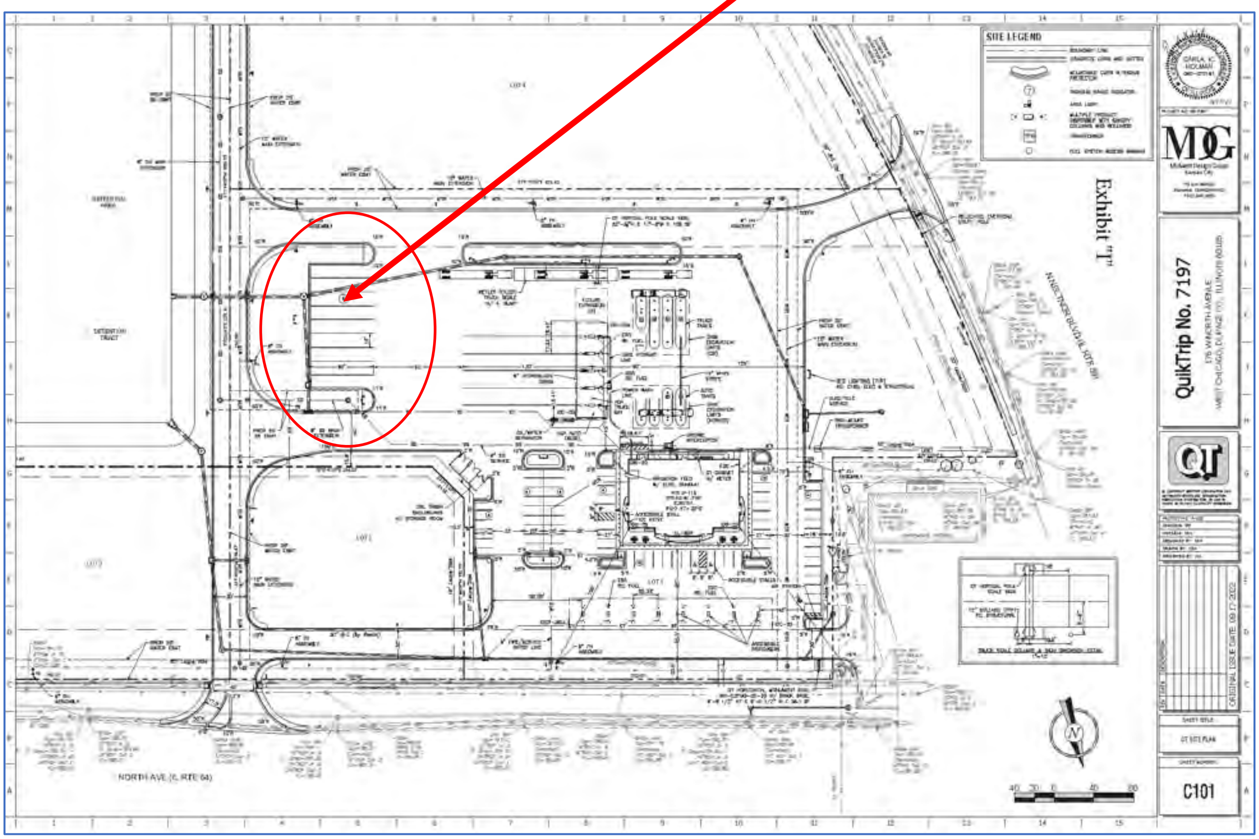


PROPOSED QUIKTRIP TRAVEL CENTER

On page 2, of the October 4, 2022, Report for the West Chicago Plan Commission/Zoning Board of Appeals, the project is described as:

> "The petitioner is proposing a commercial development known as QuikTrip Crossing with four commercial lots. The development will have three entrances including a right-in/right-out/left-in on Illinois Route 64, a right-in/right-out on Illinois Route 59, and a signalized full access on Illinois Route 59 that will be located across from Heritage Woods Drive. The petitioner is proposing a Motor Vehicle Service Station on Lot 1 that will include gas pumps for passenger vehicles, diesel pumps for trucks, a truck scale, and a "QuikTrip" convenience store."

> The project site plan below shows what appear to be nine parking spaces for semi-trucks.



POTENTIAL PROJECT NEIGHBORHOOD IMPACTS

The potential impacts of the proposed QuikTrip Travel Center include the following:

- Adverse health effects due to benzene-diesel particulate emissions,
- Crime,
- Noise,
- Property value loss, and
- Well (ground-water) contamination.

While I could not qualify as an expert with regard to any of these impacts, in this letter I have summarized a number of scientific studies regarding each impact and have shown how the findings from each study relate to the site-specific conditions at the proposed QuikTrip Travel Center and the affected neighborhoods.

Of the various adverse effects that may result from the proposed QuikTrip Travel Center, the harm to public health is the greatest concern and the most likely to occur. Adverse health effects would result from:

- benzene and other harmful compounds released to the air from underground fuel storage tank vent pipes and during refueling at the pumps, and
- from the particulate matter emitted from diesel truck engine exhaust.

Unfortunately, there are no control measures required for new gas stations or other fueling facilities in Illinois that can reliably resolve either public health impact.

The scientific studies referenced below are attached to this letter.

BENZENE & PARTICULATE EMISSIONS PUBLIC HEALTH IMPACTS

There is a large and growing body of scientific research documenting that it is unhealthy to live near a gas station, truck stop, or other facilities with a large volume of diesel truck traffic.

Diesel Emissions & Public Health

Diesel engine particulate emissions have an adverse effect on our respiratory health. One of the best summaries of this research can be found in the Clean Air Task Force report Diesel and Health in America: The Lingering Threat[1]. Adverse health effects of diesel emissions listed on report page 9, include:

- Abnormal heart rhythms, heart attacks and atherosclerosis;
- Increased incidence of stroke;
- Permanent respiratory damage, characterized by fibrosis causing obstruction to airflow; and
- Chronic adverse effects on lung development resulting in deficits in lung function.

A table on report page 7, listed Illinois as having the 6th highest death rate in the nation due to diesel emissions. Note that these statistics are based on 1999 data. As shown in the graphic on the next page, more recent data from the Clean Air Task Force Death By Dirty Diesel website[2], shows that of the 48 lower states and the District of Columbia, Illinois has the 5th highest cancer risk due to diesel particulate emissions. West Chicago is in the area shown in the graphic on the next page with the highest diesel air pollution impact in the entirety of Illinois.

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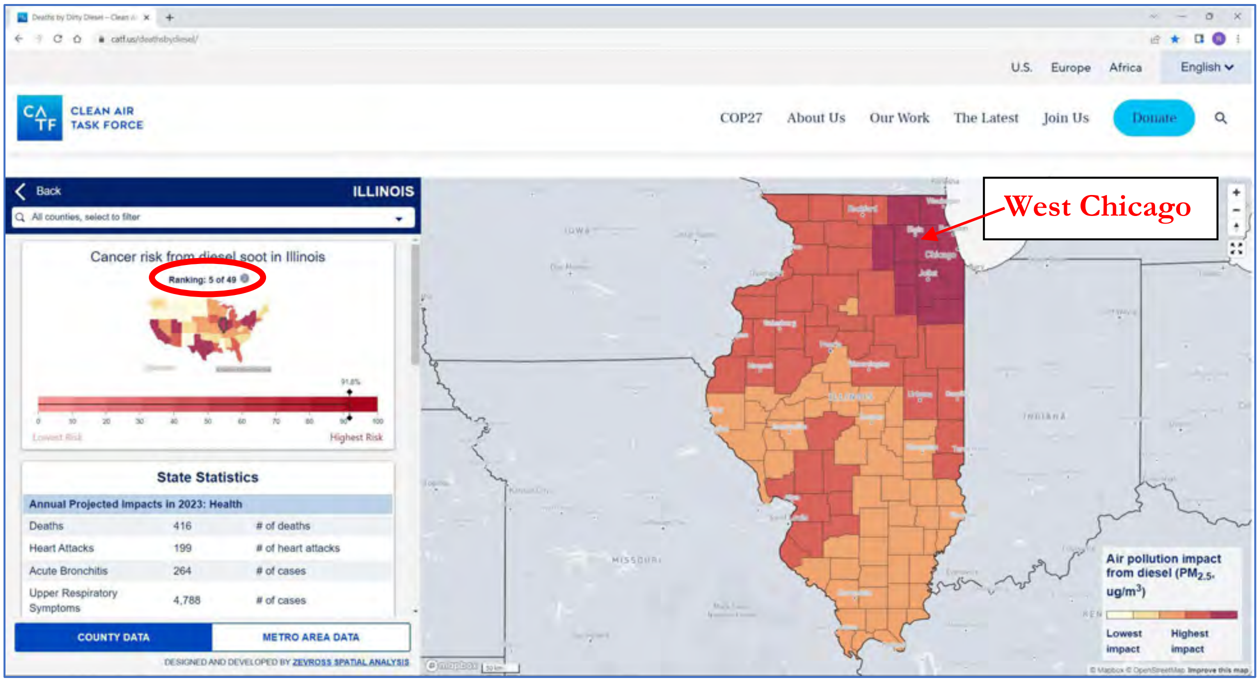
[1] See: https://www.catf.us/wp-content/uploads/2019/02/CATF_Pub_Diesel_Health_America.pdf

[2] See: https://www.catf.us/deathsbydiesel/



In the 2005 California Air Resources Board (CARB) Air Quality and Landuse Handbook[3], it was recommended (on page 11) that **homes**, schools and other sensitive land uses should be located at least 1,000 feet from any facility that would generate 100 or more diesel truck trips per day.

The October 4, 2022, Report for the West Chicago Plan Commission/Zoning Board of Appeals does not specify the number of diesel truck trips generated by the proposed QuikTrip Travel Center. In report Exhibit N, trip generation is described as:

"The proposed QuikTrip Travel Center is estimated to generate:

- 100 new trips during the weekday AM peak hour, 80 new trips during the weekday Midday peak hour, and 90 new trips during the weekday PM peak hour; and

- 370 pass-by trips during the AM peak hour, 260 pass-by trips during the Midday peak hour, and 260 pass-by trips during the PM peak hour from traffic already traveling on the adjacent roadways."

Given the traffic volume described above, it certainly seems likely that the QuikTrip Travel Center may generate more than 100 diesel truck trips daily, thus crossing the threshold where sensitive land uses (**homes**, schools, etc.) could be adversely affected within 1,000 feet.

To put the number of truck trips and possible health effects in perspective, consider that in 2021, the California South Coast Air Quality Management District[4] assessed the need to regulate diesel emissions from warehouses of 100,000 square feet or more. Such a warehouse would generate about 60 truck trips per day. The District found the impact substantial and adopted

[3] See: https://ww3.arb.ca.gov/ch/handbook.pdf
[4] See: http://www.aqmd.gov/home

a regulation[5] requiring that warehouse owners must take measures to reduce the health effects of trucks and other diesel-gasoline powered vehicles. The measures include zero[6] or near-zero emission[7] trucks. The Socioeconomic Impact Assessment[8] for this regulation noted that emissions from a warehouse with 60 diesel (semi) truck trips/day can affect the health of those living 0.5- to 2.0-miles distant. **If it is correct that the proposed truck stop will generate a 100 or so truck trips per day then the impact zone could extend beyond 1,000 feet.**

On page 3, of the October 4, 2022, Report for the West Chicago Plan Commission/Zoning Board of Appeals the following relevant staff recommendation appeared:

> "To prevent any of the truck parking stalls from being used for overnight or long-term truck parking, staff recommends that a condition be placed on the controlling ordinance prohibiting overnight parking. To enforce this condition, signage should be installed at these parking stalls indicating the prohibition."

Additionally, Illinois State statute 625 ILCS 5/11 1429[9] prohibits diesel vehicles of more than 8,000 pounds (heavy-duty trucks and buses) from idling for more than ten minutes per hour when they are parked.

While both the staff recommendation and the Illinois idling limitation could potentially reduce diesel emissions and adverse health impacts from the proposed QuikTrip Travel Center, it is unclear how much of reduction in diesel particulates would actually result even if both were strictly enforced and adhered to, which would seem unlikely.

Scientific Research Gasoline Refueling Facilities & Benzene Health Effects

A number of compounds injurious to human health are released from gas stations and other fueling facilities. These compounds include: benzene, toluene, ethyl benzene, and xylene[10]. Of these,

[5] See: http://www.aqmd.gov/docs/default-source/news-archive/2021/board-adopts-waisr-may7-2021.pdf
[6] See: https://www.edf.org/media/new-report-shows-zero-emission-trucks-buses-are-ready-roll-north-america
[7] See: https://www.socalgas.com/for-your-business/natural-gas-vehicles/near-zero
[8] See: http://www.aqmd.gov/docs/default-source/planning/fbmsm-docs/pr-2305-draft-socioeconomic-impact-assessment.pdf?sfvrsn=8
[9] See: https://www.ilga.gov/legislation/ilcs/fulltext.asp?DocName=062500050K11-1429
[10] See: https://www.ncbi.nlm.nih.gov/pubmed/26435043

benzene is the gasoline constituent most harmful to human health. Gas station benzene releases occur at the pump and from underground storage tank vents.

Adverse health effects of benzene include cancer, anemia, increased susceptibility to infections, and low birth weight. According to the World Health Organization Guidelines for Indoor Air Quality[11], there is no safe level for benzene. As explained later in this letter, measures to reliably resolve these adverse health effects are not routinely employed at new gas stations in Illinois.

In 2005, the California Air Resources Board became the first agency in the U.S. to recommend a minimum public health safety zone between new gas stations and "sensitive land uses such as residences, schools, daycare centers, playgrounds, or medical facilities." The recommendation appeared in the Air Quality and Land Use Handbook: A Community Health Perspective[12]. The State of California is widely recognized as having some of the most effective air pollution control requirements in the nation. Yet even with California controls a minimum separation between a gas station and homes is still needed to protect public health.

The U.S. Environmental Protection Agency echoed concerns about the health risk associated with gas station emissions in their School Siting Guidelines[13]. The USEPA recommended screening - but not excluding - school sites for potential health risk when located within 1,000 feet of a gas station.

The safety zone distances were prompted by the growing body of research showing that adverse health effects are found to extend further and further from gas stations with each new study.

A seminal 2015 study, Hydrocarbon Release During Fuel Storage and Transfer at Gas Stations: Environmental and Health Effects[14], contained the following summary regarding the health implications of living near a gas station:

> *"Health effects of living near gas stations are not well understood. Adverse health impacts may be expected to be higher in metropolitan areas that are densely populated. Particularly affected are residents nearby gas stations who spend significant amounts of time at home as compared to those who leave their home for work because of the longer period of exposure. Similarly affected are individuals who spend time close to a gas station, e.g., in close by businesses or in the gas station itself. Of particular concern are children who, for example, live nearby, play nearby, or attend nearby schools, because children are more vulnerable to hydrocarbon exposure."*

A 2019 study, Vent pipe emissions from storage tanks at gas stations: Implications for setback distances[15], of U.S. gas stations found that benzene emissions from underground gasoline storage tank vents were sufficiently high to constitute a health concern at a distance of

[11] See: https://www.ncbi.nlm.nih.gov/books/NBK138708/
[12] See: https://ww3.arb.ca.gov/ch/handbook.pdf
[13] See: https://www.epa.gov/sites/production/files/2015-06/documents/school_siting_guidelines-2.pdf
[14] See: https://www.ncbi.nlm.nih.gov/pubmed/26435043
[15] See: https://www.sciencedirect.com/science/article/pii/S0048969718337549

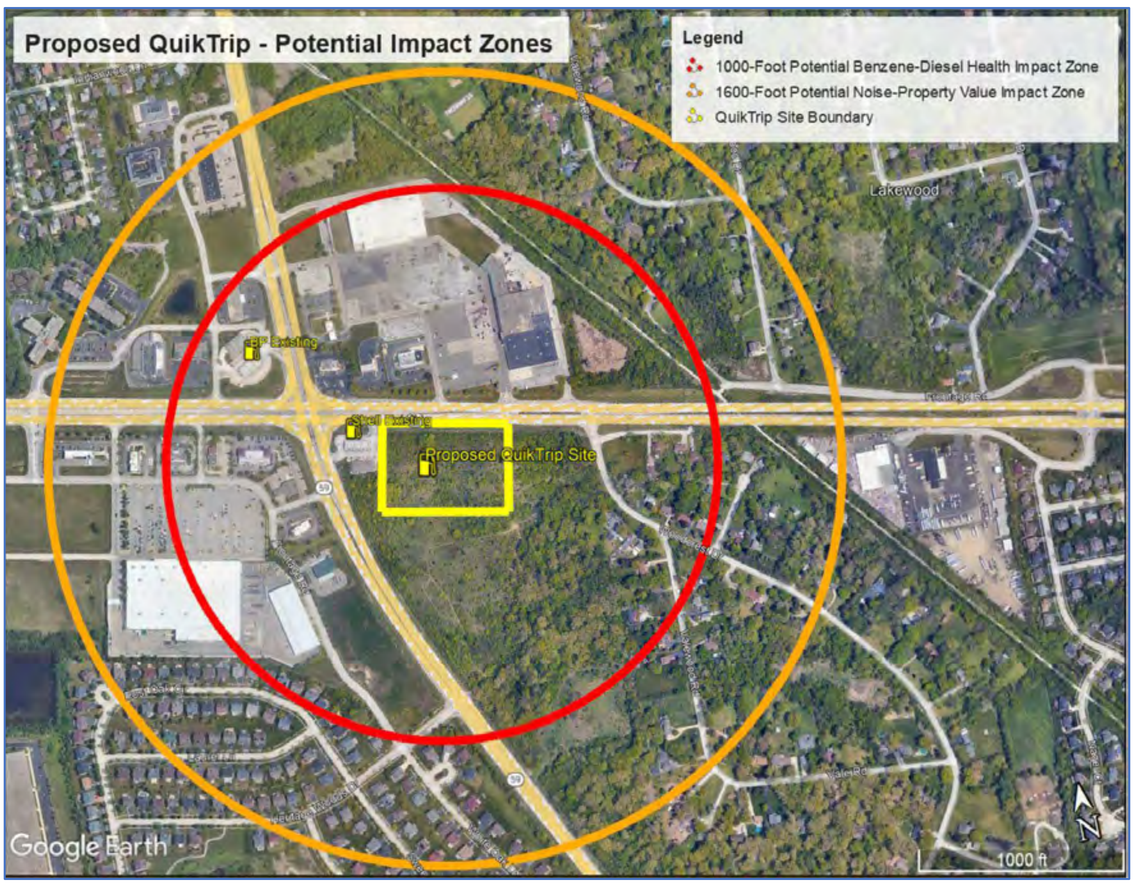
at least 524-feet. Also, the researchers noted:

> "…*emissions were 10 times higher than estimates used in setback regulations* [like that in the California handbook] *used to determine how close schools, playgrounds, and parks can be situated to the facilities [gas stations]*."

Prior to the 2019 study it was thought that most of the benzene was released at the pump during fueling.

Presence of Existing Gas Stations Magnifies Adverse Health Impact Potential

A study published in 2021, Benzene emissions from gas station clusters: a new framework for estimating lifetime cancer risk[16], documented that the cancer risk is increased when nearby residents were exposed to benzene releases from more than one nearby gas station. The aerial below shows that there are two existing gas stations in the immediate vicinity of the proposed QuikTrip Travel Center – a BP and a Shell station. The findings from the 2021 study indicate that adding a third gas station - the proposed QuikTrip Travel Center - will magnify the health threat to area residents.



[16] See: https://pubmed.ncbi.nlm.nih.gov/34150235/#:~:text=We%20found%20that%20clusters%20of,6%20for%20one%20gas%20station.

Control Measures Will Not Resolve Benzene Health Threat
The two most common control measures for gas stations are Stage II Vapor Recovery[17] and Onboard Refueling Vapor Recovery[18] (ORVR).

A decade ago, most gas pump nozzles were designed to capture vapors released during refueling. The vapors were then sent to the 10,000- to 20,000-gallon underground tanks where gasoline is stored. These Stage II vapor recovery systems were phased out beginning in 2012 as a result of the widespread use of Onboard Refueling Vapor Recovery (ORVR) systems.

As the name implies, Onboard Refueling Vapor Recovery systems are built into new cars. The system captures vapors during refueling which are then stored in canisters within the vehicle.

A 2020 study, Gasoline Vapor Emissions During Vehicle Refueling Events in a Vehicle Fleet Saturated With Onboard Refueling Vapor Recovery Systems: Need for an Exposure Assessment[19], by Dr. Markus Hilpert and others examined the effectiveness of Onboard Refueling Vapor Recovery systems. The researchers found that 88% of vehicles monitored released vapors during refueling despite the presence of Onboard Refueling Vapor Recovery systems.

The 2019 study cited previously in this letter addressed the release of benzene from underground gasoline storage tank vents. The 2019 study documented that the amount of benzene released was substantial and could be detected at a distance of up to 524 feet.

Discussions with Illinois EPA Bureau of Air Quality officials indicate that Illinois does not require measures that might resolve the public health impact. Therefore, the only available measure which can minimize adverse health effects of benzene emissions is to guide new gas stations to locations where the site is up to 1,000-feet from homes, schools, and other location where people regularly spend extended periods of time, especially the young and old.

In summary, it is for the reasons outlined above that a gas station and truck stop where fuel is dispensed should not be located within 1,000 feet of homes, especially at a location, like that proposed, where two existing gas stations are so close.

CRIME
I understand that area residents are concerned about the possibility of increased crime should the QuikTrip Travel Center be approved with the proposed truck parking facilities.

While the Federal Bureau of Investigation Crime Data Explorer[20] does not provide data specific to truck stops, it does show that of 137,556 robberies committed in 2020, three uses common to truck stops were the fourth, sixth and seventh highest robbery locations:

- Convenience stores – 13,721 robberies; 10% of all 2020 robberies,

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[17] See: https://www3.epa.gov/region1/airquality/gas.html
[18] See: https://en.wikipedia.org/wiki/Onboard_refueling_vapor_recovery
[19] See: https://www.ncbi.nlm.nih.gov/pmc/articles/PMC7020915/
[20] See: https://crime-data-explorer.app.cloud.gov/pages/explorer/crime/crime-trend

- Gas stations – 7,006 robberies; 5% of all 2020 robberies, and
- Restaurants – 5,642 robberies; 4% of all 2020 robberies.

Two of the three above uses are proposed for the QuikTrip Travel Center. If ready-to-eat food is also served with tables and chairs inside then the third use – restaurant – would also be present. The key question though is whether locating a convenience store, gas station or restaurant next to a neighborhood, as the applicant proposes, increases crime rates in nearby homes.

There is a body of research indicating that the sale of alcohol at convenience stores increases the likelihood of crime and other issues onsite and nearby. This research is summarized at the CEDS *Crime & Alcoholic Beverage Outlets* webpage: https://ceds.org/alcohol/. If beer, wine or liquor sales are allowed at the proposed QuikTrip Travel Center then area neighborhoods could be affected by increased crime.

The National Human Trafficking Hotline website includes a webpage focusing on Truck Stop-Based Trafficking: https://humantraffickinghotline.org/sex-trafficking-venuesindustries/truck-stop-based. Following is a description of the issue from this webpage:

> "Sex trafficking occurs at truck stops in the United States often in two forms, through commercial sex and through fake massage businesses. Due to their frequently remote locations and transient customer base, truck stops are an ideal venue for traffickers seeking to profit from exploiting victims without interference or undue attention. Traffickers frequently move their victims from city to city, forcing victims to engage in commercial sex at truck stops along the way. Brothels disguised as massage businesses are also sometimes present at or ***near truck stops***. These networks control women through confinement and complicated debt bondage schemes."

Further background on this issue can be found in Sex Trafficking at Truck Stops[21], by the Polaris Project. Organizations like the NATSO (National Association of Truck Stop Operators) has developed guidance such as Combating Human Trafficking. It is possible that steps such as prohibiting alcohol sales and measures recommended by NATSO, the Polaris Project and others could substantially reduce crime associated with truck stops like the proposed QuikTrip Travel Center.

NOISE, LIGHTS & OTHER NUISANCES

There's a large body of scientific evidence regarding the environmental effects of diesel truck emissions and truck facilities. In contrast, there's little data on what it's like to live near a truck stop.

To address this knowledge gap, several years ago CEDS surveyed those living in the vicinity of existing truck stops. Our Midwest clients were concerned about one of the more common truck stop chains. We identified 14 truck stops for this specific chain in the Midwest. We thought it unlikely a truck stop would affect those living a half-mile or more away. Of the 14, only six of the

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[21] See: https://humantraffickinghotline.org/sites/default/files/Sex Trafficking at Truck Stops AAG.pdf

truck stops were within a half-mile of a home. We sent a letter to those living in the vicinity of these six truck stops. Included with each letter was a self-addressed, stamped postcard. We asked recipients to note on the postcard any benefits or negative effects they experienced due to the truck stop then drop it in the mail. We received responses from those living near three (50%) of the six truck stops. All of the responses noted that truck stop noise adversely affected their quality of life. **Most of the neighbors also reported adverse effects due to light trespass, air pollution, and property value loss.** With regard to air quality, one neighbor reported:

> "Our carbon monoxide detector went off occasionally in the house; was determined to come from outside."

The homes affected by these impacts were located 400- to 2,000-feet from a truck stop. In the survey we also asked neighbors about any beneficial effects of having a truck stop nearby. Only one neighbor reported a benefit, which was "fuel and gasoline always available."

In summary, area residents at half of the truck stops reported adverse impacts due to a truck stop. From the survey and other research, it appears that truck stop noise and other impacts should not be significant at homes located at least 1600-feet distant.

Because of impacts such as these, some jurisdictions, such as Covington, Louisiana[22], require that new truck stops must be a minimum of 2,000 feet from a residential zone, park, school, day care center, library or religious or cultural activity. Meridian, Idaho[23] requires "The use shall be located a minimum of six hundred (600) feet from any residential district and a minimum of one thousand (1,000) feet from any hospital."

As shown in the aerial on the first page of this letter, there nearly a hundred homes within the 1600-foot impact zone (orange line).

PROPERTY VALUE

A truck stop may reduce the value of nearby residential properties due to noise, light trespass, or by simply being visible from nearby homes.

With regard to noise, researchers concluded the following in a 2021 study, An Analytical Framework for Evaluating Potential Truck Parking Locations[24]:

> "Increases in noise pollution are inevitable in such a case where dispersed idling trucks are centralized into the new or expanded truck stops...

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22 See: https://library.municode.com/la/covington/codes/code_of_ordinances?nodeId=PTIICOOR_APXBCOZOOR2010_PT5SPPR_S5.6TRST

23 See: https://library.municode.com/id/meridian/codes/code_of_ordinances?nodeId=TIT11UNDECO_CH4SPUSST_11-4-3-20FUSAFAFUSAFATRST

24 See: https://scholarsjournal.net/index.php/ijier/article/view/3334

Mandated by the Federal Highway Administration, maximum noise levels for large trucks are not to exceed 85 dBA (decibel) 50 feet away. Combined, this data can be used to approximate sound values over different distances. For every 2.5 dBA increase in noise levels above 55 dBA, residential property values are assumed to decrease by 0.2% to 1.2% with wealthier communities, containing higher willingness to pay for peace and quiet, being more sensitive to such increases in noise pollution (Palmquist, 1980). Any truck stop development project will require a noise impact study that evaluates the feasibility of installing noise barriers to remediate the noise pollution problem."

Simple noise models, such as the Distance Attenuation Calculator[25], indicate that it would require a separation distance of 1600 feet for the 85-decibel noise from idling diesel truck engines to drop to the residential property acceptable level of 55 decibels.

While there appears to be little independent research regarding the property value effect of the proposed gas station-convenience store, here are a couple of articles giving an anecdotal indication:

Cemeteries, highways, gas stations[26]: "Here's what decreases your property value: Gas stations, railroad tracks, hydro towers, power stations, and industrial areas — proximity to any of these things definitely won't help improve your home value, since they can generate and/or attract odors or other substances that could affect your air quality."

10 Industries That Diminish Property Values The Most[27]: "2. Convenience Store With Gas Station. People will be driving in and out of your intersection, hanging out at the property, and buying lots of lotto tickets, cigarettes, and beer when they gas up. Although handy, these shops do nothing to help property values and hurt them significantly according to Zillow.com. Although the realtors questioned on the site did not have exact statistics, common sense would show that the increase in robberies, accidents, traffic and pedestrians would add up to decreased property value. Still, many gas stations with mini-markets are springing up like wildfire."

WELL-GROUNDWATER CONTAMINATION

A number of those living to the southeast of the QuikTrip Travel Center site obtain their household water from wells and are concerned about the possibility of well contamination with gasoline or diesel fuel. These wells are located downhill and down-groundwater-gradient from the site.

According to the Illinois State Geological Survey Illinois Water and Related Wells[28] website, these wells are relatively shallow and tap into a limestone aquifer. The U.S. Geological Survey webpage on Karst (limestone) aquifers noted:

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25 See: https://www.omnicalculator.com/physics/distance-attenuation

26 See: https://www.lowestrates.ca/blog/homes/cemeteries-highways-gas-stations-can-decrease-property-value

27 See: https://housely.com/industries-that-diminish-property-values-the-most/

28 See: https://prairie-research.maps.arcgis.com/apps/webappviewer/index.html?id=e06b64ae0c814ef3a4e43a191cb57f87

"Karst terrain is created from the dissolution of soluble rocks, principally limestone and dolomite. Karst areas are characterized by distinctive landforms (like springs, caves, sinkholes) and a unique hydrogeology that results in aquifers that are highly productive but **extremely vulnerable to contamination**." [emphasis added]

There are two potential causes of groundwater contamination from gas and diesel fueling stations:

- Leakage from underground fuel storage tanks and dispenser connecting lines, and
- Spillage at dispenser pumps.

Underground Storage & Dispenser Connecting Line Leakage

The proposed QuikTrip Travel Center site plan shows a number of underground storage tanks (UST) for gasoline and diesel fuel. I assume these will be 10,000- to 20,000-gallon tanks.

Historically, fuel leaking from USTs has been a major cause of well and groundwater contamination. In response to the gas station fuel leakage issue, some U.S. states began as early as 1984 to require that new or replacement USTs have a double-walled or secondary containment systems as opposed to the former single-walled tanks.

In 2016, double-walled/secondary containment systems became a national requirement: https://www.epa.gov/ust/secondary-containment-and-under-dispenser-containment-2015-requirements. It is thought that these measures greatly reduced the likelihood of underground storage tank leakage at new gasoline-diesel fueling locations.

Spillage at the Dispenser Pump

While the design of both tanks and connecting lines has improved dramatically over the past couple of decades, a 2014 Johns Hopkins University study, Infiltration and evaporation of small hydrocarbon spills at gas stations[29], found that an average of 40 gallons of gasoline is spilled annually at the pumps of a typical gas station. Of greater concern to well owners is that the JHU researchers also found that a significant portion of the spilled gasoline can migrate through the concrete pads present at most gas station dispenser pump islands. Once the gasoline travels through the concrete, groundwater contamination may occur. Of course, the spilled gas which doesn't migrate to groundwater could be washed off by stormwater into nearby surface waters.

In conclusion, while double-walled fuel storage tanks and improved containment systems have reduced the likelihood of groundwater and well contamination, the likelihood is not zero. When combined with spillage at the pump, the potential exists for well contamination due to the proposed QuikTrip Travel Center.

The figures on the next page show how gasoline spillage-leakage at the pump could travel from the proposed QuikTrip to wells serving homes to the east and southeast.

[29] See: https://www.sciencedirect.com/science/article/pii/S0169772214001417

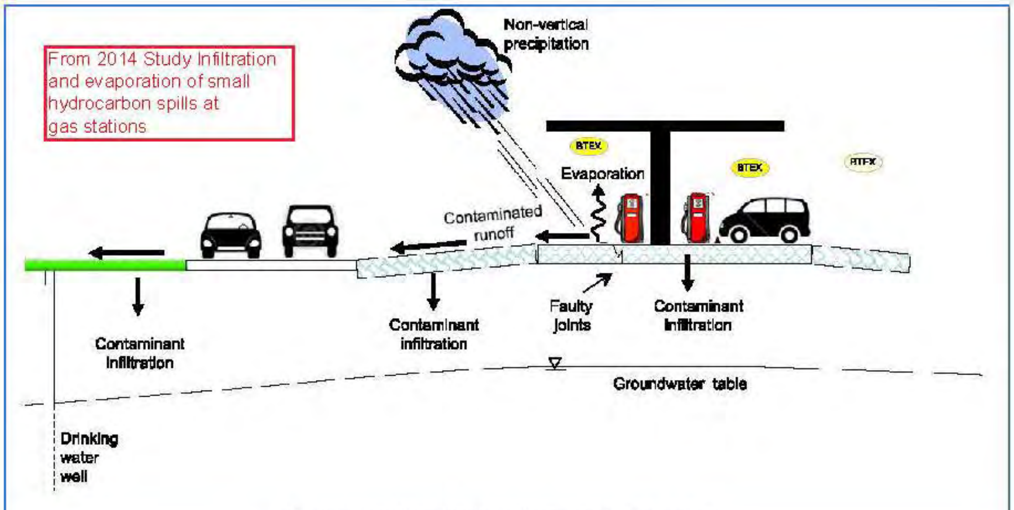


Fig. 2. Conceptual model of fate and transport of spilled gasoline.

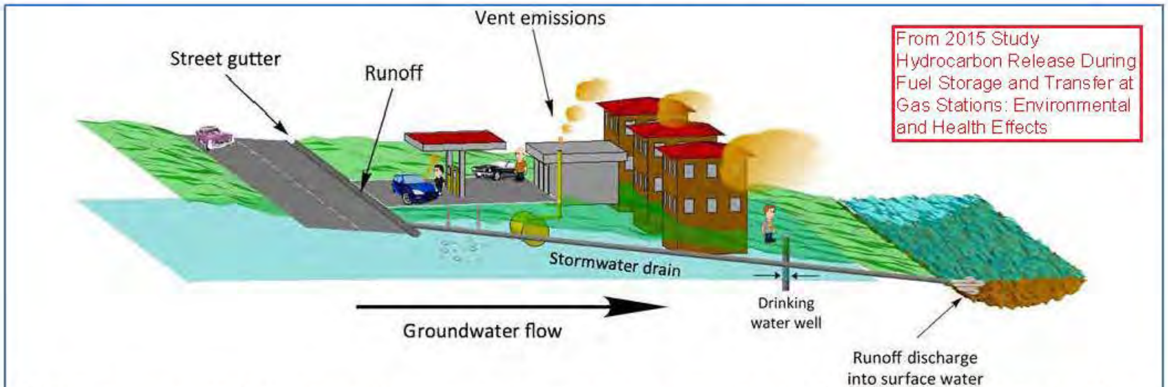
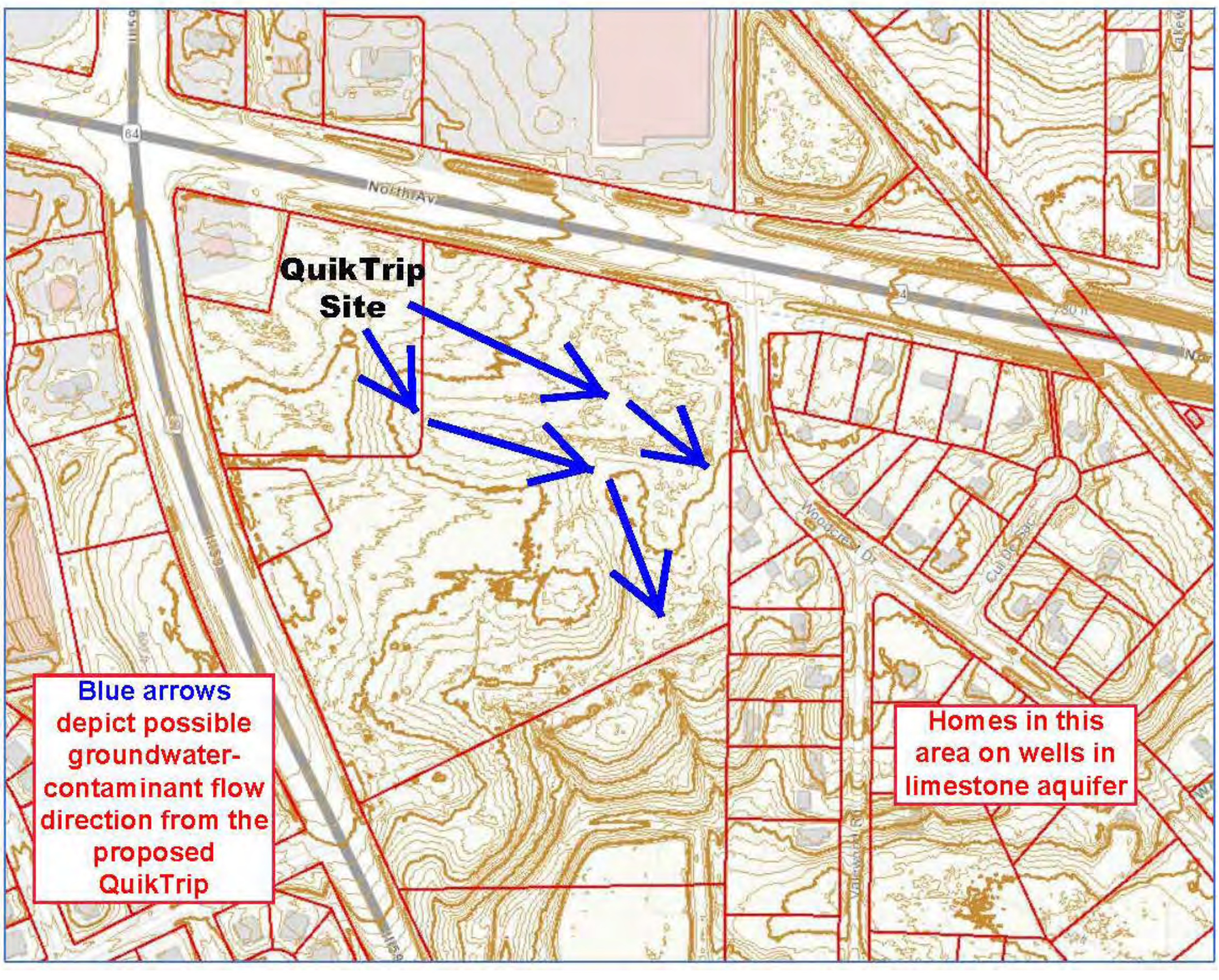


Fig. 1 Gas stations are embedded into the natural environment and can consequently release pollutants to the atmosphere, the subsurface including soil and groundwater, and surface water



QUIKTRIP TRAVEL CENTER POTENTIAL IMPACT SUMMARY

The research presented in this letter and how the research relates to site-specific conditions along with those in potentially affected neighborhoods show that there is a legitimate cause for concern that the proposed QuikTrip Travel Center could result in:

- Adverse health effects due to benzene and diesel particulates released to the atmosphere,
- Excessive noise due to idling diesel trucks and loss of property value,
- A possibility of increased crime spilling over into nearby neighborhoods, especially if alcoholic beverages are sold, and
- The possibility of the contamination of wells down-groundwater-gradient of the site.

I can be reached at 410-654-3021 or Rklein@ceds.org if you have any questions.

Sincerely,

Richard D. Klein

2014 Study
Infiltration and evaporation of small hydrocarbon spills at gas stations

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Infiltration and evaporation of small hydrocarbon spills at gas stations

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ABSTRACT

Small gasoline spills frequently occur at gasoline dispensing stations. We have developed a mathematical model to estimate both the amount of gasoline that infiltrates into the concrete underneath the dispensing stations and the amount of gasoline that evaporates into the typically turbulent atmosphere. Our model shows that the fraction of infiltrated gasoline can exceed the fraction that evaporates from the sessile droplets. Infiltrated gasoline then evaporates and is slowly released to the atmosphere via slow diffusive transport in pores. Tentative experiments show that our theoretical approach captures observed experimental trends. Predictions based on independently estimated model parameters roughly describe the experimental data, except for the very slow vapor release at the end of Stage II evaporation. Our study suggests that, over the lifespan of a gas station, concrete pads underneath gas dispensing stations accumulate significant amounts of gasoline, which could eventually break through into underlying soil and groundwater. Our model also shows that lifetimes of spilled gasoline droplets on concrete surfaces are on the order of minutes or longer. Therefore contamination can be carried away by foot traffic or precipitation runoff. Regulations and guidelines typically do not address subsurface and surface contaminations due to chronic small gasoline spills, even though these spills could result in non-negligible human exposure to toxic and carcinogenic gasoline compounds.

1. Introduction

Gas stations are potential sources of environmental contamination because liquid hydrocarbons are transferred from one container to another, e.g., when vehicle tanks are filled with fuel, when underground storage tanks for fuel are refilled, or when lubricants (e.g., motor oil) are applied to vehicles. During each liquid hydrocarbon transfer, hydrocarbon vapors are released into the atmosphere because of interphase mass-transfer from the liquid into the gaseous phase. Moreover, liquid hydrocarbon spills may occur and result in droplets/liquid masses falling onto the ground. The numerous hydrocarbon stains that can typically be found at gas stations (Fig. 1a) suggest that spills are not rare events. Indeed, an American Petroleum Institute-sponsored study in which fuel spillages at US gas stations with and without Stage II vapor recovery systems were observed found that non-trivial amounts of gasoline are spilled on a routine basis (Mueller, 1989; Wixtrom and Brown, 1992). Since Stage II vapor recovery systems are no longer required by the US Environmental Protection Agency (EPA), we report here only on spills at stations without such systems. According to the study, 0.9 g and 2.4 g of liquid gasoline were on average released when refueling a motor vehicle with and without topping off the tank, respectively. Once on the ground, liquid hydrocarbon may infiltrate into the ground which typically consists of relatively impermeable concrete, contaminate precipitation runoff that flows in sheets over the concrete, or evaporate into the open atmosphere. Fig. 2 illustrates our conceptual understanding of these processes.

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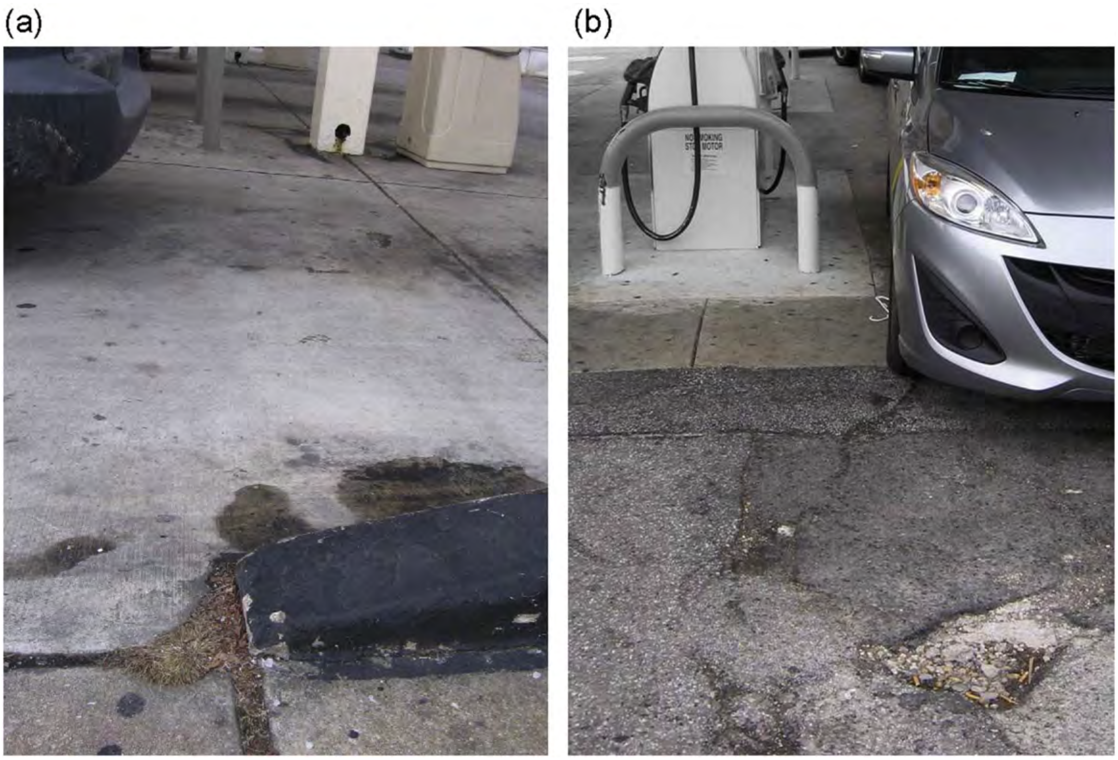

Fig. 1. (a) Concrete pads at gas stations are often covered by numerous hydrocarbon stains that in this case are even present on an adjacent public sidewalk. (b) Pavement close by dispensing stations can be cracked or damaged and could facilitate the transfer of spilled hydrocarbon into the subsurface.

Spilled hydrocarbon may end up in different environmental compartments listed below, in all of which humans can potentially be exposed to the hydrocarbons.

1. Hydrocarbon vapors may be inhaled.
2. Liquid hydrocarbon droplets/masses that sit on the ground surface or that become dissolved in runoff water can result in negative health effects if the contaminated liquid is ingested, or if dermal or eye contact occurs. Such exposure is particularly relevant to playing children.
3. The same exposures can occur if the aforementioned liquids infiltrate into soil on or with which children play.
4. Gasoline, which infiltrates into the ground and eventually ends up in groundwater, can get ingested if the groundwater

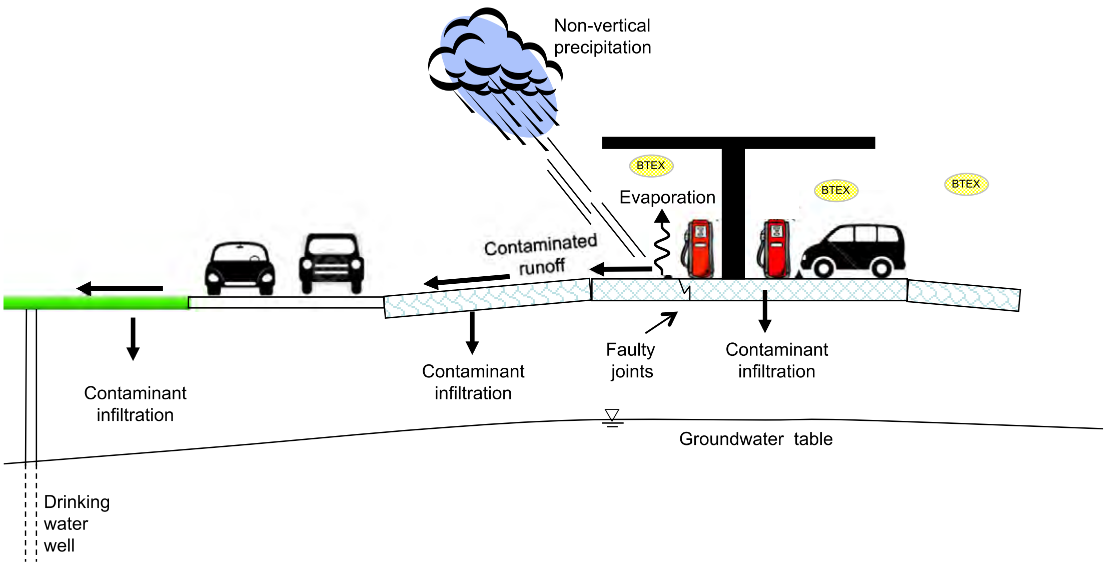

Fig. 2. Conceptual model of fate and transport of spilled gasoline.

is used as a drinking water supply. This exposure scenario is particularly prevalent in rural areas of the US.

Hydrocarbon exposure can be harmful to human health, because gasoline, one of the liquids of interest, contains toxic and carcinogenic compounds, namely benzene, toluene, ethylbenzene, and xylenes, also known as BTEX (International Agency for Research on Cancer, 1998). Environmental policies therefore seek to reduce human exposure to hydrocarbons accidentally spilled at gas stations. Special attention has been given to leakage of underground storage tanks, which can result in major releases of liquid hydrocarbons to the subsurface and massive groundwater contamination (Dowd, 1984; Squillace and Moran, 2007). There is also consensus that gasoline vapors should be avoided as inhaled hydrocarbons are harmful to human health, not only because of their direct carcinogenicity and toxicity (Bravo et al., 2002; Correa et al., 2012; Eitaki et al., 2011; Hakkola and Saarinen, 2000; Kearney and Dunham, 1986; Lagorio et al., 1994; Vainiotalo et al., 1999) but also because they contribute to unhealthy ground-level ozone (U.S. EPA, 2008). Therefore Stages I and II vapor recovery systems have been installed in gas station equipment and Onboard Refueling Vapor Recovery (ORVR) systems in vehicles to reduce the release of fuel vapors to the atmosphere and subsequent human exposure to the vapors. Furthermore, the maximum allowable Reid vapor pressure of gasoline is regulated by the US EPA during summer months. There also appears to be a consensus that the direct infiltration of gasoline that is frequently spilled in small quantities at gas dispensing stations into soil and underlying groundwater should be avoided, even though this objective is usually not directly stated. An exception is the New Hampshire (NH) Department of Environmental Services which points out that small spills of fuel that routinely occur when fuel is being dispensed to vehicles are also a main source of concern (New Hampshire Department of Environmental Services, 2012). Therefore the ground in the fuel dispensing area is typically covered by relatively impermeable concrete.

In conclusion, design guidelines for gas stations are typically not very clear about the exact purpose of concrete pads underlying gas dispensing stations. For instance, it is not spelled out what quantity of spilled liquid gasoline may infiltrate into the concrete and whether there is a percentage threshold for the fraction of infiltrated gasoline that may not be exceeded. Moreover, regulators have typically not addressed subsurface contamination due to chronic small gasoline spills, even though these contaminations could cause non-negligible human exposure to toxic and carcinogenic gasoline compounds. At the same time, surprisingly little research has been done that would allow one to predict the amount of gasoline that infiltrates or is released as vapor into the turbulent atmosphere when small quantities of gasoline are spilled onto porous ground. Even if spill volumes have been labeled as small (e.g., 3.2 L in the study by (Dakhel et al., 2003)), very little research has been devoted to the much smaller spill volumes (on the order of mL) which our study addresses and which require a different modeling approach. Such modeling capability is crucial in order to estimate human exposure to spilled gasoline, to identify relevant exposure pathways, and to evaluate changes in exposure due to damaged concrete pads or pavement at gas stations, which can occasionally be observed (see Fig. 1b).

In this paper, we present a mathematical model that evaluates quantitatively the role of infiltration into concrete pads and of evaporation into turbulent atmosphere to explain the disappearance of spilled gasoline droplets from the ground. The model can be used to estimate lifetimes of spilled, sessile gasoline droplets, the fractions of infiltrated and evaporated gasoline, and back diffusion of infiltrated gasoline into the atmosphere. This model can also be used to assess the potential pathways for human exposure.

2. Modeling

2.1. Droplet infiltration modeling

We developed a mathematical model that describes the dynamics of spilled gasoline droplets which concurrently infiltrate into an underlying porous medium and evaporate into turbulent atmosphere. This model makes the following simplifying assumptions.

1. We model the porous medium as a bundle of vertical capillary tubes, an assumption frequently made in droplet infiltration modeling (Denesuk et al., 1993; Hilpert and Ben-David, 2009). This model is basically equivalent to the Darcy-scale Green-Ampt approach (Green and Ampt, 1911), which assumes a sharp wetting front during infiltration.
2. Our model does not describe the initial and short impact phase during which inertial flows may take place. Neglecting this process is justified since little evaporation and infiltration occurs in this initial phase when compared to the period of time during which the droplet shape is determined by capillary equilibrium. The initial contact angle of gasoline on the porous concrete surface, θ_0, lies somewhere between the receding and advancing equilibrium contact angles.
3. We assume the contact line on the concrete surface to be pinned, i.e., the drawing area to remain constant during droplet evaporation/infiltration.
4. We assume the contact angle on the porous medium to be uniform and the droplet to be axisymmetric in capillary equilibrium.
5. In a first approximation, we model the complex gasoline mixture by a one-component liquid, which does not change composition and hence saturated vapor pressure and viscosity during evaporation.

Fig. 3 illustrates our model and assumptions stated above.

The mathematical model is based on a mass balance equation which relates the rate of change of the total liquid mass, m_l, to the potential rate of evaporation, $E_{po} \geq 0$ [kg m^{-2} s^{-1}]:

$$\frac{dm_l}{dt} = -\pi R_d^2 E_{po} \quad (1)$$

where R_d is the drawing radius, and t is time. The total liquid mass has two contributions:

$$m_l(t) = m_{sd}(t) + m_{in}(t) \quad (2)$$

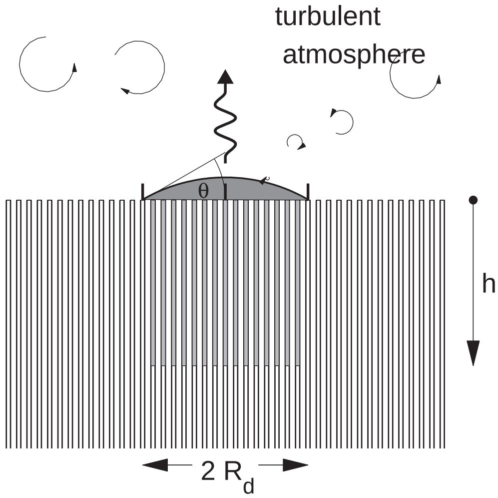

Fig. 3. Our mathematical model accounts for gasoline infiltration into the concrete (modeled as a bundle of capillary tubes) and for evaporation into the turbulent atmosphere.

where m_{sd} is the mass of the sessile droplet sitting on the external surface of the porous medium, and m_{in} is the mass of liquid that infiltrated into pores.

In order to determine the drawing radius R_d for a given initial droplet volume $V_0 = V_{sd}\,(t = 0) = m_0/\rho$ where m_0 is the initial droplet mass and ρ is the density of liquid gasoline, one must determine the droplet shape. To do so, Young–Laplace's equation for the curvature of the gas–liquid interface, the hydrostatic pressure distribution in the liquid, and the initial contact angle θ_0 must be taken into account. For the assumed axial symmetry, the droplet shape including R_d can be determined by numerically solving a system of three ordinary differential equations (del Rio and Neumann, 1997). The parameters that affect the droplet shape are θ_0, ρ and the interfacial tension between gasoline and air, σ. Appendix A shows the details of this procedure.

The mass of the infiltrated liquid is given by an explicit equation in time (Denesuk et al., 1993):

$$m_{in}(t) = \varepsilon\rho\pi R_d^2 h(t) \tag{3}$$

where ε is the porosity,

$$h(t) = A\sqrt{t} \tag{4}$$

is the height of the gasoline slug, $A = \sqrt{R_p \sigma cos\theta_{pm}/(2\eta)}$, R_p is the pore radius, η is the dynamic viscosity of gasoline, and θ_{pm} is the contact angle of gasoline within the concrete.

Eq. (3) is only valid as long as there is a supply of liquid to the porous medium, i.e., if $m_{sd} > 0$. Infiltration and evaporation of the droplet stop at a time t_l, the lifetime of the sessile droplet. This time is determined by $m_{sd}(t_l) = 0$. Therefore $m_{in}(t_l) = m_l(t_l) = m_0 - \pi R_d^2 E_{po} t_l$. This is a quadratic equation of the unknown $u = \sqrt{t_l}$ from which one can determine the lifetime of the sessile droplet:

$$t_l = \left[-\frac{\varepsilon\rho A}{2E_{po}} + \sqrt{\left(\frac{\varepsilon\rho A}{2E_{po}}\right)^2 + \frac{m_0}{\pi R_d^2 E_{po}}} \right]^2. \tag{5}$$

From this time, one can calculate integral measures for the contaminant distribution before gasoline evaporates from the concrete back into the atmosphere. At time t_l, the fraction of liquid evaporated is given by

$$\frac{m_{ev}}{m_0} = \frac{\pi R_d^2 E_{po}}{m_0} t_l \tag{6}$$

while the fraction of liquid infiltrated is given by $m_{in}/m_0 = 1 - m_{ev}/m_0$.

2.2. Potential evaporation modeling

An important input parameter to our model is the potential rate of evaporation E_{po}. To estimate it, we adapted Penman's approach for water evaporation from wet surfaces. As compared to mass-transfer based approaches (Navaz et al., 2008), Penman's approach has the advantage that wind speed and temperature need to be measured at only one elevation (Brutsaert, 2005). Modeling droplet evaporation represents a slight abuse of Penman equation, because it was developed to estimate water evaporation from a large wet surface such that the vapor density (humidity for water) depends only on the elevation but not on the horizontal coordinates. This assumption is not fulfilled for a droplet. Nonetheless, applying Penman's equation to droplet evaporation can be justified, because Penman's equation has also been used in the theory of complementary fluxes to estimate evaporation from evaporation pans, which also sit on a typically drier porous medium (Brutsaert and Stricker, 1979).

It is straightforward to apply Penman's equation to a liquid other than water. The potential rate of evaporation is then given by

$$E_{po} = \frac{\Delta}{\Delta + \gamma} \frac{Q_n}{L_e} + \frac{\gamma}{\Delta + \gamma} E_A \tag{7}$$

where $\gamma = \frac{c_p p}{L_e M_v/M_d}$ is the psychrometric constant, Δ is the slope of the saturated vapor pressure–temperature curve, Q_n is the available energy flux density, M_v/M_d is the ratio of the molar masses of the vapor and dry air, L_e is the latent heat of evaporation, $E_A = f_e(\overline{u}_r)(e_a^* - \overline{e}_a)$ is the drying power of air, f is a wind function which depends on a wind velocity u_r, $\overline{e}_a$ is the vapor pressure of gasoline in air, and e_a^* is the saturated vapor pressure of gasoline (Brutsaert, 2005). We note that Brutsaert in the expression for the psychrometric constant γ, replaces M_v/M_d by 0.622, the ratio of the molar masses of water vapor and dry air. For f_e one can employ empirical relations which, however, are only valid for water vapor. Therefore we use rigorously derived equations which are valid for any vapor.

One example is the following relation which is valid in a neutral atmosphere:

$$f_e(\overline{u}_1) = \frac{\frac{M_v}{M_d} k^2 \overline{u}_1}{R_{dr} T_a ln\left(\frac{z_2 - d_0}{z_{0v}}\right) ln\left(\frac{z_1 - d_0}{z_0}\right)} \quad (8)$$

where $k = 0.41$ is the Karman constant, z_1 is the elevation at which the wind velocity $\overline{u}_1$ is measured, z_2 is the elevation at which $\overline{e}_a$ is measured, z_0 is the momentum roughness length, z_{0v} is the roughness length for the vapor, d_0 accounts for uncertainties in defining the position of a rough surface, T_a is the air temperature, and R_{dr} is the specific gas constant for dry air.

The variables in Penman's theory which do not depend on the type of liquid evaporated are R_{dr}, k, z_0 and T_a. The constants that depend on the liquid are e_a^*, Δ, L_e, M_v/M_d, z_{0v} and γ. Next we describe how numerical values can be chosen for the latter group of variables in order to describe evaporation of gasoline. The latent heat of evaporation for gasoline is $L_e = 316.6$ kJ/kg at 300 K (Zhang and Kong, 2010). For the significant temperature dependence of the saturated vapor pressure of gasoline, we used the data measured by (Yoshida et al., 2012) shown in Fig. 4. In order to estimate e^* as well as the slope $\Delta = de^*/dT$ for any temperature T, we fitted the Antoine model to the data:

$$log_{10} e^* = A - \frac{B}{T + C} \quad (9)$$

where e^* is measured in units of Torr, and T in units of °C. The best-fit parameters were $A = 6.644$, $B = 1106$ and $C = 239$. The slope of the saturated vapor pressure–temperature curve is then given by $\Delta = ln(10)\frac{B}{(T+C)^2}e^*$. The molar mass of gasoline vapor is $M_v \approx 105$ g/mol (EPA, 2013), while the molar mass of dry air is $M_d \approx 29$ g/mol. With $p = 10^5$Pa, $c_p = 1006$ J/(kg K), we obtain $\gamma = 1151$ Pa/K. The roughness length for a vapor, z_{0v}, can be expected to be a function of the roughness of the surface, the viscosity of air, the vapor diffusivity, and finally the surface shear stress (Brutsaert, 1975). For water vapor, the simplifying assumption $z_{0v} = z_0/10$ is often employed (Brutsaert, 2005). Since the diffusion coefficient of gasoline vapor, e.g., $D_{ma} = 7 \times 10^{-7}$ m^2/s (Al Zubaidy et al., 2013), is roughly equal to the one of water vapor (10^{-6} m^2/s), the Schmidt numbers for the two vapors are also about equal. Therefore theoretical considerations (Brutsaert, 1975) suggest that $z_{0v} = z_0/10$ is also a reasonable approximation for gasoline vapor.

We are now able to come up with numerical values for all parameters in Penman's equation as applied to the evaporation of gasoline. To get an idea about the order of magnitude of E_{po} that one can expect, we examined the temperature dependence of E_{po} for an assumed available energy flux density $Q_n = 100$ W/m^2 and a wind velocity $\overline{u} = 2$ m/s at 2 m above ground. Fig. 5 shows that evaporation rates for gasoline are much higher than those observed for water which rarely exceed 10 mm/day. The main reason for the difference lies in the high saturated vapor pressure e^* of gasoline which is an order of magnitude higher than the one for water, and the low latent heat of evaporation which is an order of magnitude lower than the one for water. Therefore, both the equilibrium and the nonequilibrium evaporations, which are represented by the first and second terms in Eq. (7), are higher for gasoline than for water.

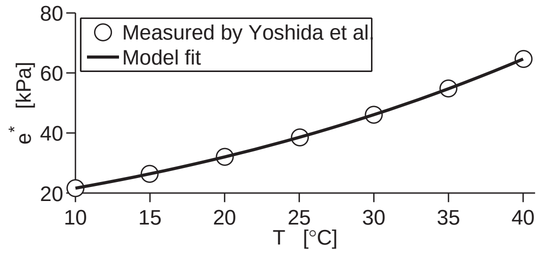

Fig. 4. Vapor pressure e* of gasoline as a function of temperature *T*.

2.3. Drying modeling

Once the sessile droplet has vanished at time t_l, liquid gasoline in the concrete will evaporate and diffuse through the pores back into the atmosphere, but also into deeper concrete layers. To obtain first quantitative clues about how much gasoline is released, we employ an evaporation modeling approach which assumes that the gasoline, which can occur in different fluid phases (as a liquid or vapor in soil air), is locally in thermodynamic equilibrium (Charbeneau, 2006). Then the following equation is valid for the bulk gasoline concentration ρ_b [kg/m^3]:

$$\frac{\partial \rho_b}{\partial t} = D_T \frac{\partial^2 \rho_b}{\partial z^2} \quad (10)$$

where $D_T = \frac{\theta_a \tau_a D_{ma}}{B_a} + \frac{\theta_w \tau_w D_{mw}}{B_w} + \frac{\theta_g \tau_g D_{mg}}{B_g}$ [m^2/s] is the total effective diffusion coefficient of the multiphase system, and the B's, D_m's and τ's are the bulk partitioning coefficients, molecular diffusion coefficients, and tortuosity factors, respectively, for the air, water, and gasoline phases. The effective diffusion coefficient accounts for diffusive transport in all fluid phases; however, diffusion in the air phase constitutes the main contribution. Like (Charbeneau, 2006), we can therefore assume a constant diffusion coefficient

$$D_T = \varepsilon^{1/3} D_{ma}/B_a \quad (11)$$

which basically assumes dry conditions (absence of both water and liquid gasoline) and the (Millington and Quirk, 1961) model for tortuosity. The bulk air partition coefficient is given by $B_a = \rho_b/\rho_v$ where ρ_v [kg/m^3] is the saturated gasoline vapor concentration. The latter can be calculated from the ideal gas equation $\rho_v = e^* M_v/(R_0 T)$ where R_0 is the universal gas constant. Eq. (11) can be expected to perform quite well in regions where most of the liquid gasoline has already evaporated.

We assume the initial condition

$$\rho_b(z, t = 0) = \rho_{b0}[\Theta(z) - \Theta(z - z_0)] \quad (12)$$

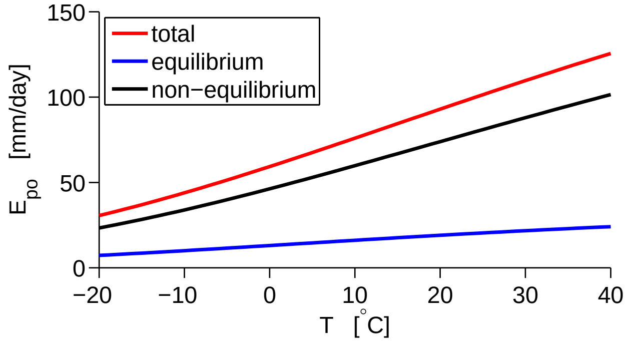

Fig. 5. Sample evaporation rates E_{po} for gasoline as a function of temperature T estimated from Penman's equation.

where $\rho_{b0} = \rho\varepsilon$ is the initial bulk density of gasoline, $z_0 = h(t_l)$, and Θ is the Heaviside step function. This initial condition conforms to the final stage of infiltration, according to which the soil is uniformly wetted down to a depth $h(t_l)$. The boundary condition is assumed to be $\rho_b(z=0, t>0) = 0$ and means that any gasoline vapor reaching the soil surface is immediately diluted by uncontaminated atmospheric air currents. We obtained the solution to Eq. (10) subject to the given boundary and initial conditions by the method of Laplace transformation (please see Appendix B for details). The bulk concentration ρ_b as a function of depth z and time t is given by

$$\rho_b(z,t) = \frac{\rho_{b0}}{2}\left[\mathrm{erfc}\left(\frac{z_0+z}{2\sqrt{D_T t}}\right) - \mathrm{erfc}\left(\frac{z_0-z}{2\sqrt{D_T t}}\right) + 2\mathrm{erf}\left(\frac{z}{2\sqrt{D_T t}}\right)\right] \tag{13}$$

for $z < z_0$ and

$$\rho_b(z,t) = \frac{\rho_{b0}}{2}\left[\mathrm{erfc}\left(\frac{z_0+z}{2\sqrt{D_T t}}\right) + \mathrm{erfc}\left(\frac{z-z_0}{2\sqrt{D_T t}}\right) - 2\,\mathrm{erfc}\left(\frac{z}{2\sqrt{D_T t}}\right)\right] \tag{14}$$

for $z \geq z_0$. The rate of evaporation is the negative mass flux density at the ground surface and can be computed from Fick's law: $E_c(t) = D\frac{\partial \rho_b}{\partial z}\big|_{z=0} = \sqrt{\frac{D_T}{\pi t}}\rho_{b0}\left\{1-\exp\left(-z_0^2/(4D_T t)\right)\right\}$. The subscript c indicates potential conditions, under which E_c can assume arbitrarily large values, which are not limited by the atmosphere's ability to carry away the gasoline vapors. From this expression, we can determine the cumulative evaporation under potential conditions:

$$F_c(t) = \int_0^t E_c(t')dt' = \rho_{b0}\left[z_0\mathrm{erfc}\left(\frac{1}{2\sqrt{\tau}}\right) + 2\sqrt{\frac{D_T t}{\pi}}\left(1-e^{-\frac{1}{4\tau}}\right)\right] \tag{15}$$

[kg/m^2] where $\tau = t/t_{diff}$ is a nondimensional time, and

$$t_{diff} = z_0^2/D_T \tag{16}$$

is a typical time scale for evaporation and diffusion of infiltrated gasoline to the concrete surface. The cumulative evaporation converges to $F_c(t\rightarrow\infty) = \rho_{b0}z_0$.

Eq. (15) yields an initially infinite and hence unphysical rate of evaporation, and for some period of time also a rate of evaporation that exceeds the maximum possible potential evaporation E_{po}. To resolve this issue, the time condensation method (Salvucci and Entekhabi, 1994) can be employed. This method basically assumes that drying initially occurs with the potential rate of evaporation for a period of time termed the time of evaporative capacity, t_{ec}, and that for times $t \geq t_{ec}$ evaporation can be described by Eq. (15). This is an approximation, because the state at time t_{ec} has not been reached through a process described by Eq. (15). With these assumptions, the cumulative evaporation due to drying of the porous substrate becomes

$$F_{dr}(t) = \begin{cases} E_{po}t & \text{for} \quad t < t_{ec} \\ F_c(t-t_{ec}+t_{cr}) & \text{for} \quad t \geq t_{ec} \end{cases} \tag{17}$$

where the constraint $F_{dr}(t_{ec}) = E_{po}t_{ec} = F_c(t_{cr})$ ensures continuity of $F_{dr}(t)$ at $t = t_{ec}$, and drying is still assumed to start at time $t = 0$. Different approaches for estimating t_{ec} and t_{cr} exist (Brutsaert, 2005). In the absence of experimental data, dF_{dr}/dt is often assumed to be continuous, in addition to F_{dr}. Subsequent application of the equations $E_{po} = E_c(t_{cr})$ and $F_c(t_{cr}) = E_{po}t_{ec}$ can then be used to determine first t_{cr} and then t_{ec}. If one finally accounts for the fact that drying of the concrete starts when the life time of the droplet, t_l, has been reached, the masses of infiltrated and evaporated liquid are for times $t \geq t_l$ given by

$$m_{in}(t) = \pi R_d^2[\varepsilon\rho h(t_l) - F_{dr}(t-t_l)] \tag{18}$$

$$m_{ev}(t) = \pi R_d^2\left[t_l E_{po} + F_{dr}(t-t_l)\right]. \tag{19}$$

2.4. Sample simulation

Fig. 6 shows results from a sample simulation that illustrates the different phases that a droplet experiences after being deposited on a porous surface. Simulation parameters have been chosen such that the three phases can be clearly distinguished, because the duration of Stage I evaporation is typically much smaller than that of Stage II evaporation. At first,

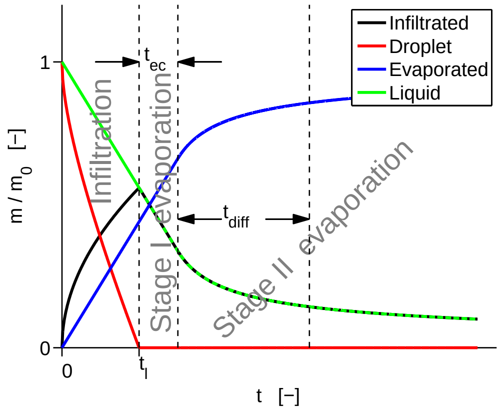

Fig. 6. Three phases of droplet infiltration and evaporation: (1) infiltration and simultaneous evaporation occurs until the lifetime of the sessile droplet, t_l, is reached; (2) then gasoline evaporates from the concrete under potential conditions for a period of time termed the time of evaporative capacity, t_{ec}; and (3) finally evaporation is limited by the gasoline supply and gradually approaches a value of zero at a typical time scale t_{diff}. All masses are normalized by the initial gasoline mass m_0.

the droplet is present as a sessile droplet that infiltrates and evaporates until the lifetime of the droplet, t_l, is reached. Then Stage I evaporation begins, during which gasoline continues to evaporate from the porous substrate into the atmosphere under potential conditions. During this phase, the rate of evaporation is constant and controlled by atmospheric conditions. Thereafter, during Stage II, evaporation continues but is limited by the gasoline supply from the porous substrate (Or et al., 2013). The amount of the previously infiltrated liquid gradually decreases and approaches a value of zero.

3. Simulations

We first performed a base case simulation in order to develop a tentative quantitative understanding about how infiltration and evaporation typically contribute to the disappearance of a sessile gasoline droplet on a concrete pad. For the permeability of concrete, we used $\kappa = 1.4 \times 10^{-20}$ m^2, the lowest water permeability measured by Jacobs (1994) who examined the effects of composition and atmospheric humidity on concrete properties. We can use the permeability–radius relation for a bundle of capillary tubes, $\kappa = \varepsilon R_p^2/8$, to backcalculate an effective pore radius which is $R_p = 0.9$ nm. Also according to Jacobs, we used a porosity $\varepsilon = 0.15$. From this value, Eq. (11), and fluid properties from Section 2.2, the effective soil diffusion coefficient becomes $D_T = 6.9 \times 10^{-8}$ m^2/s. For the contact angle within the porous medium, we assumed $\theta_{pm} = 20°$. For the viscosity, we assumed $\eta = 0.5 \times 10^{-3}$ kg m^{-1} s^{-1}. For interfacial tension, we used $\sigma = 21 \times 10^{-3}$ N/m (Wang et al., 2006). Moreover, we assumed a spill volume of 1.25 mL, the gasoline volume that according to Mueller (1989) is released on average during vehicle refueling (without topping-off). For the evaporation rate we assumed 100 mm/day, which is a representative value for the rates that we estimated with Penman's equation (see Fig. 5). For the initial contact angle between gasoline and air on the concrete surface we assumed a value of $\theta_0 = 20°$. This assumption is probably reasonable for dry (no water) concrete, because oil-based liquids are usually the wetting fluid in comparison to air. As shown in Fig. 7a, almost one half of the gasoline infiltrates into the concrete despite its very low permeability. This can be attributed to the capillary action which gives rise to a huge driving force during the initial phase of infiltration (Hilpert, 2009; Hsu and Hilpert, 2011; Pellichero et al., 2012; Washburn, 1921). Since the total droplet volume is so small, the slow, late phase slow of infiltration is not reached. From the simulation, one can also see that the droplet vanishes from the surface after about 4 min. This period of time is long enough to allow for cross-contamination through foot traffic. Once the sessile droplet is gone, gasoline evaporates within the concrete and is slowly released to the atmosphere. The typical time scale for this process is $t_{diff} = 40$ min, a time much larger than the combined lifetime of the sessile droplet and time of evaporative capacity. Significant tailing of the gasoline vapor concentration is observed after this typical diffusion time. It takes 1.5 h until 90% of the deposited gasoline has evaporated from the concrete.

Next we performed three simulations in which we varied either the spill volume V_0, the initial contact angle on the concrete surface, θ_0, or the rate of evaporation, E_{po}. Table 1 shows how these three simulations differ from the base case simulation. Simulation results are shown in Fig. 7b, c and d, respectively.

For a smaller evaporation rate, $E_{po} = 20$ mm/day, a value that could be representative of a cold winter day, it takes longer (about 8 min) for the droplet to vanish, because droplet removal through evaporation is less effective. As a consequence the amount of infiltrated gasoline is much higher, about four times the volume of gasoline evaporated. It also takes much longer for the gasoline to evaporate from the concrete into the atmosphere. In fact, it takes about 7.5 h until 90% of the initially deposited gasoline has been released from the concrete. This is to some extent due to the smaller potential evaporation. A more important contributing factor is that the typical diffusion time increased to $t_{diff} = 89$ min, because the gasoline reached a greater depth z_0.

Wettability also has a profound impact on droplet fate. We increased the initial contact angle to $\theta_0 = 90°$. More gasoline evaporates because the decreased drawing area results in slower droplet removal in terms of both infiltration and evaporation. While the rate of evaporation is not affected by the longer duration, the rate of infiltration is, and it decreases. This is because with time the decelerating viscous forces overcome the accelerating capillary forces. Again it takes much longer, 3.2 h, to evaporate 90% of the deposited gasoline when compared to the base case, because the infiltration depth z_0 is greater due to the smaller drawing area.

When the spill volume is increased by a factor of five, i.e., $V_0 = 6.25$ mL, the ratio between infiltrated and evaporated liquid remains roughly the same, because the average initial droplet height $\bar{h}$ is not affected much as the initial droplet volume changes as also shown in Table 1. We note that this conclusion cannot be drawn if one does not account for the effects of gravity on droplet shape. For droplets with a large drawing area and volume, it is therefore crucial to account for gravity.

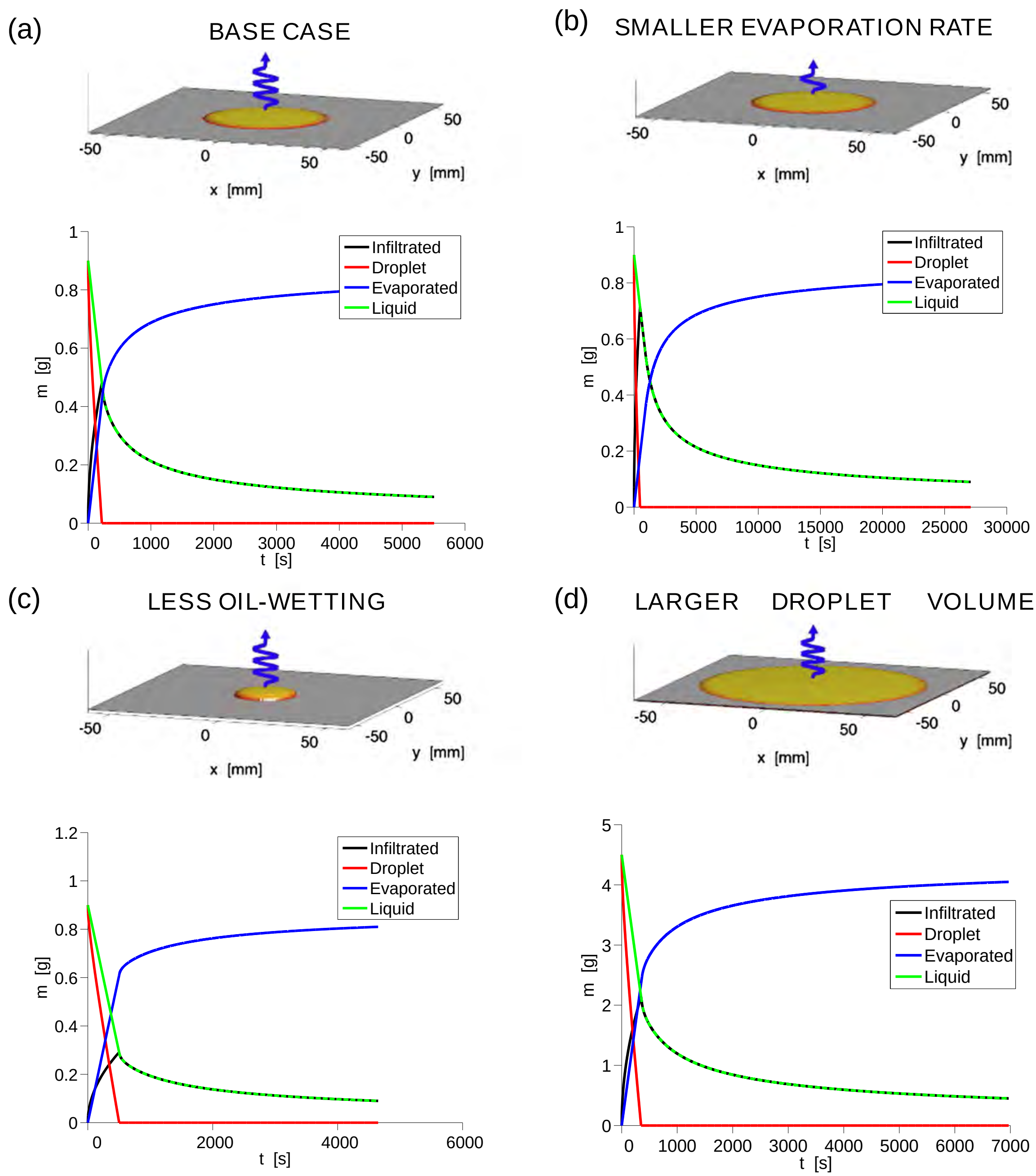

Fig. 7. Simulation of infiltration and evaporation of a volatile gasoline droplet into concrete for 4 different initial conditions (top plots). Wettability and evaporation rate have a profound impact on the ratio between gasoline in the liquid and vapor phases. The droplet volume has a lesser effect.

Table 1
Simulation parameters.

	Case #1	Case #2	Case #3	Case #4
θ_0 [degrees]	20	20	90	20
V_0 [mL]	1.25	1.25	1.25	6.25
R_d [mm]	27.1	27.1	13.6	58.9
$\bar{h}$ [mm]	0.54	0.54	2.1	0.57
E [mm/day]	100	20	100	100

The four scenarios illustrate that the contributions of evaporation and infiltration to the disappearance of spilled gasoline droplets are on the same order of magnitude when the life time t_l of the sessile droplet has been reached. This is coincidental, because the cumulative infiltration scales in a diffusion-like manner like the square root of time t according to Eq. (4), while the cumulative evaporation scales linearly with t. To understand better at which points evaporation or infiltration

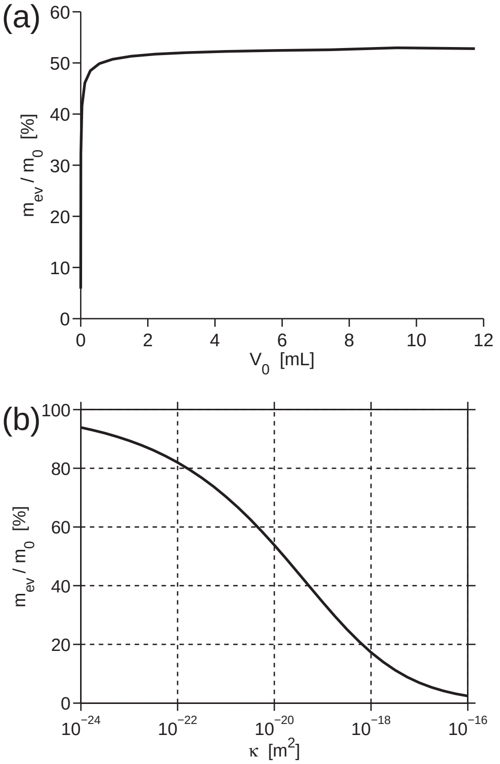

Fig. 8. (a) The fraction of gasoline evaporated, m_{ev}/m$_0$, levels off when the spill volume V_0 is increased. (b) m_{ev}/m$_0$ amounts to about 50% for the lowest permeability of concrete observed by Jacobs (1994) for a spilled droplet with a 0.9 g mass.

dominates, we performed simulations that examined how the spill volume V_0 and concrete permeability κ affect the fraction of gasoline evaporated, m_{ev}/m_0, where all other simulation parameters are the ones from the base case. Fig. 8a demonstrates that the fraction of gasoline evaporated increases with the spill volume V_0 and levels off. Interestingly, evaporation and infiltration contribute about equally to the disappearance of gasoline droplets as V_0 becomes large. Fig. 8b shows that a reduction in permeability must be substantial in order to reduce significantly the percentage of gasoline infiltrated. To reduce m_{in}/m_0 to 10%, one would need to lower κ by about two orders of magnitude. At the same time, a significant increase in m_{in}/m_0 requires increasing κ by several orders of magnitude. In real-world applications, a significant increase in κ due to cracks and faulty joints between concrete pads appears to be more likely than a significant decrease.

4. Preliminary experiments

We performed preliminary laboratory experiments in order to evaluate the suitability of the proposed modeling approach. We obtained concrete samples from sidewalk repair work in Baltimore City. An angle grinder was used to prepare pieces with surface areas < 100 cm^2. Concrete samples were stored in the lab for several weeks and appeared to be dry before infiltration experiments were performed.

Experiments were performed at room temperature under a fume hood to prevent exposure to harmful gasoline vapors. Each concrete sample was placed on a balance (Ohaus SP602) with the upper surface of the concrete being level. To record mass as a function of time, the balance was connected to a computer. Then the balance was zeroed, data collection started, and a gasoline droplet (87 octane) of initial mass $m_0 \approx 1$ g was applied to the upper surface of the concrete sample. The measured mass represented the total amount of liquid gasoline m_l on and in the concrete sample that was present as a sessile droplet or as infiltrated gasoline, respectively. Data were collected for about 8 h.

Fig. 9 shows results from four experiments which are representative of a larger number that we performed. Most of the early mass data can be described by a linear relationship. Only for a short period of time at the very beginning was the evaporation rate higher. This could be due to the enhanced evaporation of gasoline components with a higher vapor pressure. There is a point in time when the data can no longer be described by a linear relationship. According to our modeling approach this point in time is given by $t_l + t_{ec}$. For greater times, the $m(t)$ data level off, i.e., the rate of evaporation decreases. This phase represents Stage II evaporation. Extended tailing occurs. It takes many orders of magnitude longer for the gasoline to leave the concrete sample in vapor form than to invade it through liquid infiltration. It is not clear whether the $m(t)$ data asymptotically approach a value of zero.

To model the data, we visually identified $t_l + t_{ec}$. Then we fitted a linear model to the data. From the slope dm/dt, we could determine the potential rate of evaporation E_{po} via $E_{po} = \frac{1}{A_0} dm/dt$ where A_0 is the wetted area. Then we fitted the evaporation model according to Eq. (19) and the second case of Eq. (17) to the data. The $m(t)$ data alone did not allow determining t_{ec} and t_{cr} separately. Moreover, the experimental data suggest that the slope of $m(t)$ is not continuous at time $t_l + t_{ec}$. We therefore applied the time-compression method in a way that does not impose continuity of dF_{dr}/dt. We only assumed $F_{dr}(t) = F_c(t + t_0)$ where $t_0 > 0$ is a fit parameter (which is related to t_{ec} and t_{cr}) and where evaporation under conditions of limited gasoline supply was assumed to begin at time $t = 0$. The effective diffusion coefficient D_T was also used as a fit parameter. Since some of the experimental data suggested that not all of the gasoline managed to escape from the concrete (at least not during the course of the experiment), the late stage of evaporation cannot be explained by diffusive transport alone. We therefore used only part of the Stage II evaporation data to do the model fit. Specifically, we restricted ourselves to a period of time, 2 t_{diff}, during which diffusive transport of gasoline in the fluid phases could be expected to be the dominant transport mechanism. To provide a model fit for the entire Stage II evaporation data, we modified the time-compression method to account for a fraction α of the liquid gasoline mass present in the concrete at time $t_l + t_{ec}$ that is quasi-irreversibly bound to the concrete. This fraction was also used as a fit parameter. Appendix C contains details about how Eq. (17) was fitted to the experimental data.

Table 2 summarizes the parameter values used to obtain the model fits shown in Fig. 9. The measured potential evaporation rates are roughly in line with those shown in Fig. 5 predicted for a temperature $T = 20°$. Perfect agreement cannot be expected

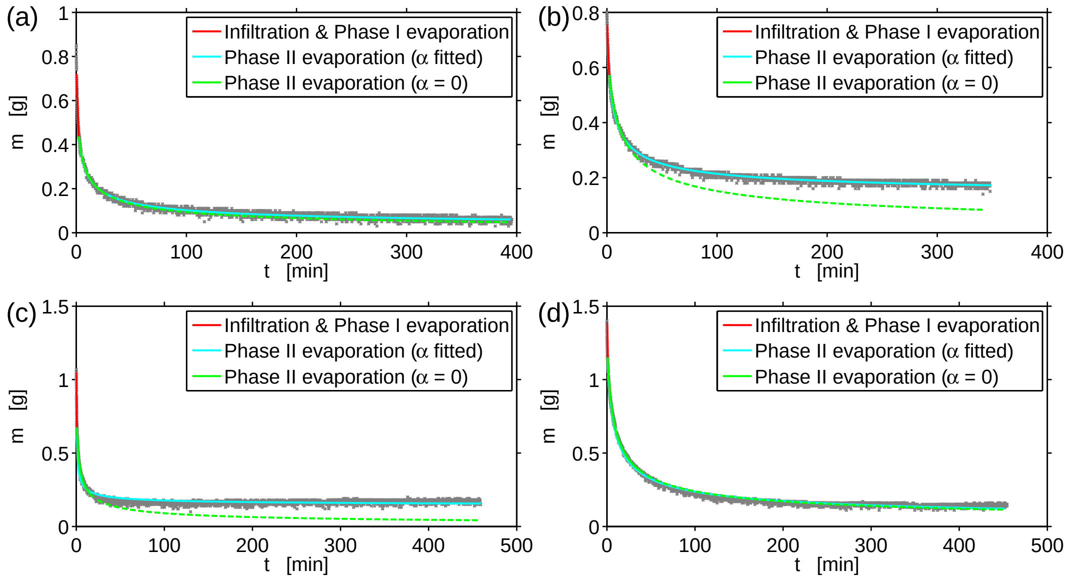

Fig. 9. Total liquid gasoline mass m as a function of time t for four experiments, in which a gasoline droplet was spilled on a concrete sample. Subfigures (a) through (d) correspond to the experimental IDs from Table 2. Symbols: experimental data. Lines: model fits. Initially, during infiltration and Phase I evaporation, the liquid mass on and in the concrete can be modeled by a linear relationship. The initial phase of Stage II evaporation can be modeled by an equilibrium diffusion model (solid green line). Extrapolation of this model (dashed green line) does not always fit the experimental data well, particularly when the liquid mass appears to converge to a positive irreducible gasoline mass in the concrete. A diffusion model which accounts for irreducible gasoline provides good model fits (blue lines).

since the wind velocity in the fume hood was not measured. However, it appears as if Penman's equation underpredicts the actual evaporation. This makes sense because Penman's equation assumes a large fetch, which allows for higher vapor concentrations in the air and hence a smaller vapor concentration gradient. The measured E_{po} fluctuated probably because the air discharge velocity in the fume hood varied between experiments. The fitted diffusion coefficients agree reasonably well (within one order of magnitude) with the independently estimated one, $D_T = 6.9 \times 10^{-8}$ m^2/s. It appears as if the estimated D_T overpredicts the fitted ones. This makes sense since the estimated D_T does not account for reduction of pore space available for vapor diffusion due to the presence of liquid gasoline.

5. Discussion

Overall, the droplet infiltration and evaporation modeling approach works quite well, except for the late phase of Stage II evaporation. Good model fits for the entire data sets can only be obtained if the model accounts for irreducible gasoline, which we quantified through the parameter α. We have unfortunately not been able to estimate this parameter independently. We suspect that α depends on the time scale of observation, as eventually all gasoline can be expected to be removed through potentially very slow diffusive transport. The latter is likely controlled by potentially nonlinear desorption processes, for which our model does not account. Estimates of droplet evaporation from Penman's equation appear to predict measurements within a factor of two better. Penman's equation offers a convenient method to estimate evaporation from standard meteorological data and can account for seasonal effects. This is important for the analysis of gasoline spills, because the composition of gasoline and its vapor pressure are seasonally dependent. As illustrated in Fig. 7, it is crucial to account for the effects of gravity on droplet shape as we did.

Surprisingly, a significant fraction of spilled gasoline droplets may infiltrate into concrete pads despite their very low permeability. This is because infiltration of a wetting liquid (contact angle <90°) into a porous medium generally occurs very fast initially. Mathematically the amount of infiltrated liquid scales initially like the square root of time t, that is, the rate of infiltration is initially infinite. Thus infiltration "wins" initially over evaporation, which is roughly constant during an infiltration event. Later on, however, infiltration slows down, as is typical for diffusion-like processes, and evaporation wins.

Table 2
Values of initial droplet mass m_0, drawing area A_0, and fitting parameters used to obtain the model fits shown in Fig. 9.

				$\alpha = 0$		Fitted α		
ID	m_0	A_0 [cm^2]	E_{po} [mm/day]	D_T [m^2/s]	t_0 [s]	D_T [m^2/s]	t_0 [s]	α [−]
Concrete_A	0.85	33	78	1.6e-08	232	1.1e-08	195	0.04
Concrete_B	0.80	28	67	8.9e-08	402	1.6e-09	57	0.22
Concrete_C	1.07	66	176	7.5e-09	100	3.2e-09	7	0.21
Concrete_D	1.40	67	118	9.3e-09	174	7.2e-08	206	0.01

Therefore the amount of liquid infiltrated may exceed the amount of liquid evaporated if the evaporation/infiltration event takes place over a sufficiently short duration. As illustrated in our modeling, this is the case for sufficiently oil-wet concrete pads for which the droplet height $\bar{h}$ is small, and for small evaporation rates E_{po}.

Infiltrated gasoline is slowly released to the atmosphere, but the experimental data suggest that it may be strongly bound to the concrete, which results in an even slower vapor release. According to Eq. (10), the vapors can also move into deeper concrete layers via molecular diffusion. Fig. 10 illustrates that the concentration maximum can move significant distances downward. Thus molecular diffusion provides another potential groundwater contamination pathway (Baehr et al., 1999; Dakhel et al., 2003).

More research is needed with regard to possible biodegradation in concrete pads. Such biodegradation is likely to occur, because microbial life can be found almost anywhere. We suspect, however, that biodegradation in concrete occurs at much lower rates than in soil because of the presence of fewer nutrients and limited electron-acceptor replenishment (due to the low permeability). Moreover, interactions between newly spilled gasoline droplets and gasoline that has already infiltrated into the concrete should be studied. It can be expected that the infiltration capacity of the concrete decreases if it is already partially saturated with gasoline. Concrete permeabilities should also be measured for gasoline and used in the model predictions. In this work, we used the concrete permeabilities measured for water. Even though permeability κ is often assumed to be independent of the fluid that flows through a porous medium, the water permeability is orders of magnitude smaller than the air permeability in concrete, because water alters the pore geometry of concrete due to chemical interactions (hydration). We believe that these interactions are less pronounced for oil-based liquids because of their typically non-polar character. Finally, predicting exposure to harmful chemicals in the gasoline mixture and associated health effects will require developing a multicomponent modeling approach, because the different chemical species have different rates of evaporation and diffusion coefficients. As a consequence, gasoline composition changes during evaporation, with the less volatile components remaining longer in liquid phase. This also results in a viscosity η that increases during the course of evaporation (Zhu et al., 2012), which in turn should increase the lifetime t_l of a sessile gasoline

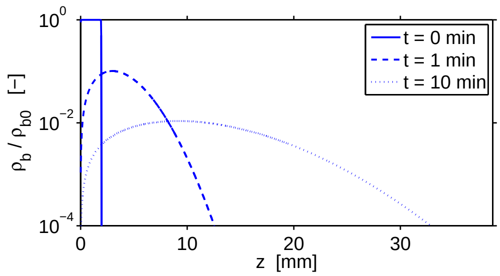

Fig. 10. Simulation of evaporation of a gasoline slug in concrete according to Eq. (10). The effective diffusion coefficient is $D_T = 6.9 \times 10^{-8}$ m^2/s, the value that we estimated for concrete. The slug is 1.9 mm long and corresponds to the base case shown in Fig. 7a.

droplet, because liquid infiltrates more slowly, as can be expected from Eq. (5) (which has been developed for a constant η).

Environmental legislation intended to minimize environmental contamination at gas stations typically ignores the possibility of gasoline infiltration due to chronic small gasoline spills, while contamination due to leakage of USTs has received much more attention. Our study shows that a significant fraction of gasoline droplets spilled on concrete pads may infiltrate into the concrete pads. Thus the concrete pads effectively retain spilled gasoline. It is not clear whether this function can be maintained over long periods of time, e.g., over the lifespan of a gas station. Since small gasoline spills occur many times per day at gas stations, these spills could cause significant accumulation of gasoline in concrete pads. To understand better the magnitude of the problem, we consider a hypothetical scenario in which a gas station sells about 400,000 L of gasoline per month. If each customer purchases 40 L to fill his/her tank, this amounts to 10,000 fillings per month. If each tank filling is on average related to 1.25 mL of spilled gasoline (Mueller, 1989), the total volume of gasoline spilled per year is 150 L, and 1500 L in 10 years. This is a non-trivial amount of gasoline that is released in a relatively small area next to filling stations. More research is needed to estimate the total fraction of gasoline that remains in the concrete and the fraction that reaches groundwater, either as a vapor or a liquid phase. 150 liters/year = 40 gallons/year

Our simulations have also shown that spilled gasoline droplets may persist in liquid phase on the surface of concrete for several minutes. We also note that the ability of concrete pads underneath the dispensing areas to absorb spilled gasoline can be impeded if the pads are covered by a thick layer of water, which fills up all the surface pores of the concrete, a condition that can, for example, be due to non-vertical rain. Gasoline cannot then be absorbed by the concrete as a liquid phase, because it is a light non-aqueous phase liquid (LNAPL) that will float on top of the denser liquid water and potentially form gasoline-contaminated runoff. Even though liquid gasoline present on concrete surfaces will eventually disappear due to volatilization, the prolonged presence of this surface contamination has not received wide attention by regulators. It does not seem advisable to walk barefoot at a gas station; however, warning signs are not common place.

6. Conclusions

Potential environmental exposure due to spilled gasoline infiltrating into concrete pads has not been studied sufficiently, even though the fraction of gasoline infiltrated can exceed the fraction evaporated. Regulators appear to have largely neglected this exposure scenario. Indeed the policy of reducing the Reid vapor pressure of gasoline for the purposes of ozone reduction leads to increased gasoline infiltration. It is possible that gasoline in concrete pads will eventually seep into underlying soil and groundwater, particularly if the concrete pads are cracked. Chronic small gasoline spills at gas stations could potentially be a significant contributing factor to the correlations observed between urbanization and contamination of groundwater by gasoline. These correlations have been well-documented for MTBE and have typically been explained by leaking underground storage tanks (Ayotte et al., 2005; Grady and Casey, 2001). However, biodegradation in the natural subsurface material underneath the concrete pads will need to be considered in future studies in order to understand fully the environmental impacts of chronic small gasoline spills that seep through concrete pads into the ground. Biodegradation can be an important contaminant removal mechanism in subsurface systems, particularly in the unsaturated zone under aerobic conditions (Lahvis et al., 1999). However, the remedial action of a subsurface microbial community depends on the specific gasoline component and is site-specific. It can be expected that there is greater opportunity for biodegradation if the groundwater table is deep due to better replenishment of the electron acceptor as shown in a study on soil vapor intrusion into buildings (Abreu and Johnson, 2006). Conversely, microbes might not be able to keep up with the flux from small gasoline spills if the groundwater table is high.

Reconsideration of design criteria for gas service stations appears to be needed, because the gas station industry is currently trending away from small-scale service stations that typically dispense around 400,000 L per month to high-volume retailers (HVR) that dispense more than 10 times this amount. Due to their size, these HVRs will provide greater opportunity for spillage and therefore represent larger sources of potential hydrocarbon contamination.

Appendix A. Droplet shape

The equilibrium shape of an axisymmetric sessile droplet can be determined from the following system of ordinary differential equations (ODEs) (del Rio and Neumann, 1997):

$$\frac{d}{ds}\begin{pmatrix} x \\ z \\ \theta \\ V \end{pmatrix} = \begin{pmatrix} \cos\theta \\ \sin\theta \\ 2b + zc - \dfrac{\sin\theta}{x} \\ \pi x^2 \sin\theta \end{pmatrix} \tag{A-1}$$

where s is the arc length, x and z are the radial and vertical coordinates of the interface, θ is the tangential angle which becomes the contact angle at the three-phase contact line of a sessile droplet, V is the volume of the sessile droplet, b is the curvature at the origin ($x = z = 0$) of the coordinate system, and $c = \Delta\rho g/\sigma$ is a capillary constant. This ODE is solved starting from the apex of the sessile droplet ($x = z = 0$). The initial conditions are therefore given by $x(s = 0) = z(s = 0) = \theta(s = 0) = V(s = 0) = 0$. If $s = 0$, the singularity for $d\theta/ds$ is eliminated by solving instead $d\theta/ds = b$. Fig. A-1 illustrates the geometry and coordinate system.

We note that the fourth component of this vector equation is not needed to determine the droplet shape, because the volume V does not appear on the right-hand-side of the ODE. However, including it offers a convenient method for obtaining the volume of the sessile droplet while determining its shape.

In our application, we needed to determine the shapes of sessile droplets for a given contact angle θ_0 between the droplet and the surface of the porous medium, and a given volume V_0. The density difference $\Delta\rho$, the surface tension σ, and gravitational acceleration g were known input parameters. The only unknown parameter was b. We therefore assumed b to be a fit parameter. To that end, we integrated Eq. (A-1) until $\theta(s) = \theta_0$ for a given b, and used the Nelder–Mead simplex method to adjust b until $V = V_0$.

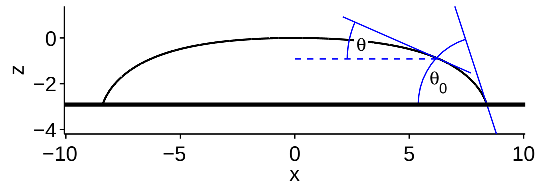

Fig. A-1. Geometry of a sessile droplet.

Appendix B. Analytical solution for stage II evaporation

The PDE for diffusion in a one-dimensional domain is given by

$$\frac{\partial u}{\partial t} = D\frac{\partial^2 u}{\partial z^2} \tag{A-2}$$

where we suppress the subscript of the diffusion coefficient, and u represents ρ_b. We wish to solve this PDE subject to the initial condition

$$u(z > 0, t = 0) = f(z) \tag{A-3}$$

and the boundary condition

$$u(z = 0, t \geq 0) = 0. \tag{A-4}$$

We are particularly interested in the initial condition

$$f(z) = f_0[\Theta(z) - \Theta(z - z_0)] \tag{A-5}$$

where $z_0 > 0$, and Θ is the Heaviside step function. However, initially we develop a solution that is valid for arbitrary f-functions.

In Laplace space, the PDE becomes an ordinary differential equation:

$$-f(z) + sU(z, s) = D\frac{d^2 U}{dz^2}. \tag{A-6}$$

The general homogeneous solution is

$$U_h(z, s) = c_1 e^{\sqrt{s/D}z} + c_2 e^{-\sqrt{s/D}z}. \tag{A-7}$$

A particular solution is

$$U_p(z, s) = \frac{1}{2D\sqrt{s/D}} \left(e^{-\sqrt{s/D}z}\int_0^z e^{\sqrt{s/D}\xi} f(\xi)d\xi - e^{\sqrt{s/D}z}\int_0^z e^{-\sqrt{s/D}\xi} f(\xi)d\xi\right). \tag{A-8}$$

Therefore the general solution to Eq. (A-6) is

$$U(z,s)=\left(c_1-\frac{1}{2D\sqrt{s/D}}\int_0^z e^{-\sqrt{s/D}\xi}f(\xi)d\xi\right)e^{\sqrt{s/D}z}+\left(c_2+\frac{1}{2D\sqrt{s/D}}\int_0^z e^{\sqrt{s/D}\xi}f(\xi)d\xi\right)e^{-\sqrt{s/D}z}. \quad (A-9)$$

To ensure that u is bounded as $z\to\infty$,

$$c_1=\frac{1}{2D\sqrt{s/D}}\int_0^\infty e^{-\sqrt{s/D}\xi}f(\xi)d\xi. \quad (A-10)$$

The boundary condition in Laplace space, $U(z=0,s)=0$, yields $c_1=-c_2$.

Finally we consider the initial condition given by Eq. (A-5). We can now evaluate all integrals in the expression for $U(z,s)$:

$$c_1=\frac{f_0}{2D\sqrt{s/D}}\int_0^{z_0} e^{-\sqrt{s/D}\xi}d\xi=\frac{1}{2s}\left(1-e^{-\sqrt{s/D}z_0}\right) \quad (A-11)$$

$$\frac{1}{2D\sqrt{s}}\int_0^z e^{-\sqrt{s/D}\xi}f(\xi)d\xi=\begin{cases}\frac{f_0}{2s}\left(1-e^{-\sqrt{s/D}z_0}\right) & \text{if} \quad z\ge z_0\\ \frac{f_0}{2s}\left(1-e^{-\sqrt{s/D}z}\right) & \text{if} \quad z\le z_0\end{cases} \quad (A-12)$$

$$\frac{1}{2D\sqrt{s}}\int_0^z e^{\sqrt{s/D}\xi}f(\xi)d\xi=\begin{cases}\frac{f_0}{2s}\left(e^{\sqrt{s/D}z_0}-1\right) & \text{if} \quad z\ge z_0\\ \frac{f_0}{2s}\left(e^{\sqrt{s/D}z}-1\right) & \text{if} \quad z\le z_0\end{cases}. \quad (A-13)$$

Therefore the solution in Laplace space becomes

$$\begin{aligned}U(z,s)&=f_0\left(\frac{1}{2s}\left(1-e^{-\sqrt{s/D}z_0}\right)-\frac{1}{2s}\left(1-e^{-\sqrt{s/D}z}\right)\right)e^{\sqrt{s/D}x}\\&+f_0\left(-\frac{1}{2s}\left(1-e^{-\sqrt{s/D}z_0}\right)+\frac{1}{2s}\left(e^{\sqrt{s/D}z}-1\right)\right)e^{-\sqrt{s/D}z}\\&=\frac{f_0}{2s}\left(-e^{\sqrt{s/D}(z-z_0)}+e^{-\sqrt{s/D}(z+z_0)}-2e^{-\sqrt{s/D}z}+2\right)\end{aligned} \quad (A-14)$$

for $z\le z_0$ and

$$\begin{aligned}U(z,s)&=f_0\left(\frac{1}{2s}\left(1-e^{-\sqrt{s/D}z_0}\right)-\frac{1}{2s}\left(1-e^{-\sqrt{s/D}z_0}\right)\right)e^{\sqrt{s/D}z}\\&+f_0\left(-\frac{1}{2s}\left(1-e^{-\sqrt{s}z_0}\right)+\frac{1}{2s}\left(e^{\sqrt{s/D}z_0}-1\right)\right)e^{-\sqrt{s/D}z}\\&=\frac{f_0}{2s}\left(e^{-\sqrt{s/D}(z+z_0)}+e^{\sqrt{s/D}(z_0-z)}-2e^{-\sqrt{s/D}z}\right)\end{aligned} \quad (A-15)$$

for $z\ge z_0$. In temporal space, the solution is given by

$$u(z,t)=\begin{cases}\frac{f_0}{2}\left[\mathrm{erfc}\left(\frac{z_0+z}{2\sqrt{Dt}}\right)+\mathrm{erfc}\left(\frac{z-z_0}{2\sqrt{Dt}}\right)-2\mathrm{erfc}\left(\frac{z}{2\sqrt{Dt}}\right)\right] & \text{for} \quad z\ge z_0\\ \frac{f_0}{2}\left[-\mathrm{erfc}\left(\frac{z_0-z}{2\sqrt{Dt}}\right)+\mathrm{erfc}\left(\frac{z_0+z}{2\sqrt{Dt}}\right)+2\mathrm{erf}\left(\frac{z}{2\sqrt{Dt}}\right)\right] & \text{for} \quad z\le z_0\end{cases}. \quad (A-16)$$

The rate of evaporation E is the negative mass flux density at the ground surface and can be computed from Fick's law:

$$E(t)=D\frac{\partial u}{\partial z}\Big|_{z=0}=\sqrt{\frac{D}{\pi t}}f_0\left\{1-\exp\left(-z_0^2/(4Dt)\right)\right\}. \quad (A-17)$$

From this expression, we can determine the cumulative evaporation:

$$\begin{aligned}F_{dr}(t)&=\int_0^t E(t')dt'\\&=f_0\left[z_0\mathrm{erfc}\left(\frac{1}{2\sqrt{\tau}}\right)+2\sqrt{\frac{Dt}{\pi}}\left(1-e^{-\frac{1}{4\tau}}\right)\right]\end{aligned} \quad (A-18)$$

where $\tau=Dt/z_0^2$ is a nondimensional time. This evaporation converges to $F(t\to\infty)=f_0z_0$.

Appendix C. Parameterization of the time-compression method

When using the time-compression method to analyze the experimental data, we cannot back out both t_{ec} and t_{cr}, because the data does not allow determining the beginning of Stage I evaporation. Therefore we assume that the cumulative infiltration during Stage II evaporation is given by

$$F_{dr}(t)=F_c(t+t_0) \quad (A-19)$$

where $t\ge 0$ and t_0 is a fit parameter. When determining z_0, we assume that all mass present at the end of Stage I evaporation is subsequently released:

$$\frac{m_1}{A_0}=F(t=\infty)-F(t=t_0). \quad (A-20)$$

This yields an implicit equation for z_0 which can be cast in a form that is suitable for solution through Picard iteration:

$$z_0=\frac{\frac{m_1}{\rho_{b0}A_0}+2\sqrt{\frac{D_Tt_0}{\pi}}\left(1-e^{-\frac{1}{4\tau_0}}\right)}{\mathrm{erf}\left(\frac{1}{2\sqrt{\tau_0}}\right)} \quad (A-21)$$

where $\tau_0=D_Tt_0/z_0^2$ on the right hand side bears the dependence on z_0.

In order to account for the retention of a certain amount of gasoline by the concrete such that a fraction $\alpha\le 1$ of the mass

m_1 remains as irreducible gasoline in the concrete, the latter equation needs to be modified in the following manner:

$$z_0 = \frac{(1-\alpha)\frac{m_1}{\rho_{b0}A_0} + 2\sqrt{\frac{D_T t_0}{\pi}}\left(1-e^{-\frac{1}{4\tau_0}}\right)}{\mathrm{erf}\left(\frac{1}{2\sqrt{\tau_0}}\right)}. \quad (A-22)$$

To fit F_{dr} to the experimental data, we first identified visually the point in time, t_2, in which the measured $m(t)$ data does not have a constant slope dm/dt anymore. This point in time was assumed to indicate the beginning of Stage II evaporation. Using the Nelder–Mead simplex method, we then fitted the measured $F_{dr}(t-t_2)$ data for $t \geq t_2$ to Eq. (A-19), where D_T, t_0, and potentially α were the fit parameters.

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2015 Study
Hydrocarbon Release During Fuel Storage and Transfer at Gas Stations: Environmental and Health Effects

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AIR POLLUTION AND HEALTH (JD KAUFMAN AND SD ADAR, SECTION EDITORS)

Hydrocarbon Release During Fuel Storage and Transfer at Gas Stations: Environmental and Health Effects

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Abstract At gas stations, fuel is stored and transferred between tanker trucks, storage tanks, and vehicle tanks. During both storage and transfer, a small fraction of unburned fuel is typically released to the environment unless pollution prevention technology is used. While the fraction may be small, the cumulative release can be substantial because of the large quantities of fuel sold. The cumulative release of unburned fuel is a public health concern because gas stations are widely distributed in residential areas and because fuel contains toxic and carcinogenic chemicals. We review the pathways through which gasoline is chronically released to atmospheric, aqueous, and subsurface environments, and how these releases may adversely affect human health. Adoption of suitable pollution prevention technology should not only be based on equipment and maintenance cost but also on energy- and health care-saving benefits.

Keywords Gas stations · Vapor emissions · Fuel spills · Adverse health effects · Pollution prevention

Introduction

The primary function of gas stations is to provide gasoline and diesel fuel to customers, who refill vehicle tanks and canisters. Operating a gas station requires receiving and storing a sufficient amount of fuel in storage tanks and then dispensing the fuel to customers. During delivery, storage, and dispensing of fuel at gas stations, unburned fuel can be released to the environment in either liquid or vapor form. Fuel is a complex mixture of chemicals, several of them toxic and carcinogenic [1]. Of these chemicals, the health consequences of chronic benzene exposure are best understood. Occupational studies have linked benzene exposures to numerous blood cancers, including acute myeloid leukemia and acute non-lymphocytic leukemia [2]. Concerns have been raised that gasoline vapor exposures incurred by gas station attendants [3] and tanker truck drivers [4] may result in health risks.

The potential for fuel released to the environment at gas stations, in the form of liquid spills or vapor losses, to elicit adverse health outcomes could be substantial due to the widespread distribution of gas stations across communities and the intensive usage of vehicle fuel in industrialized nations. For example, the USA consumed about 137 billion gallons of gasoline, or about 430 gallons per US citizen, in 2014 [5]. If only a small fraction of this gasoline was to be released to the environment in the form of unburned fuel, for instance 0.1 %, then about 1.6 L of gasoline would be released per capita per year in the USA. In Canada, a study estimated that evaporative losses at gas stations in 2009 amounted to 58,300,000 L [6]. With a population of about 34 million, we estimated that about 1.7 L of gasoline was released per capita per year in Canada from evaporative losses, without counting the liquid spills. While personal intake of this quantity of gasoline would result in serious adverse health effects, environmental dilution can decrease personal exposure. An overarching question is under which conditions dilution in the aqueous and atmospheric environments can limit personal exposures to acceptable levels. For example, cumulative adverse health effects could be more pronounced in metropolitan areas where more people

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are exposed and where the density of gas stations is larger than in rural areas.

Engineers and regulators have paid a lot of attention to leaking underground storage tanks (LUSTs) and leaky piping between storage tanks and gasoline-dispensing stations, which can result in catastrophic fuel release to the subsurface [7]. For instance, double-walled tanks have become standard in order to minimize accidental release of liquid hydrocarbon. Technologies that prevent pollution due to non-catastrophic and unreported releases of hydrocarbon that occur during fuel storage and transfer (hereafter referred to as "chronic releases"), however, have not been uniformly implemented within the developed world. The state of California in the USA has the strictest policies to minimize chronic releases, either in liquid or in vapor form. Other US states and industrialized nations, however, have not uniformly adopted California's standards, potentially because comprehensive economic and public health analyses to inform policy making are not available. This paper focuses on chronic hydrocarbon releases at gas stations (including both liquid spills and vapor losses), their contributions to human exposures and potential health risks, and factors that influence the adoption of suitable pollution prevention technology.

Chemical Composition of Fuel

Fuels have historically contained significant fractions of harmful chemicals, some of which have been documented as contributing to morbidity and mortality in exposed persons. Crude oil, from which fuels have historically been refined, already contains toxic chemicals such as benzene [8]. Fuel additives including anti-knocking agents and oxygenates have historically also been a health concern [9]. Fuel composition has changed over time, primarily due to environmental and health concerns [9]. Fuel composition also depends on geographic location and fuel type (e.g., conventional versus reformulated gasoline) [10]. In the 1920s, lead was added to gasoline as an anti-knocking agent to replace added benzene because of its carcinogenicity [11]. Due to the massive release of lead to the environment and its neurotoxicity [12], lead was replaced in the 1970s by less toxic anti-knocking agents including methyl tert-butyl ether (MTBE) [13]. To reduce formation of ground-level ozone and associated adverse respiratory health effects [14], cleaner burning of fuel was sought in the 1990s by adding oxygenates to gasoline. This was accomplished by increasing the concentrations of MTBE, which acts as an oxygenate [9]. However, MTBE accidentally released to the subsurface [15] contaminated downstream drinking water wells relatively quickly, moving almost with the speed of groundwater, because MTBE is hydrophilic and poorly biodegradable [16]. MTBE was later on identified as a potential human carcinogen [16]. In the USA, MTBE was therefore phased out in the 1990s; at the same time, refineries began supplementing fuel with ethanol as an oxygenate [17].

In current gasoline formulations, benzene, toluene, ethylbenzene, and xylene (BTEX) and particularly benzene are the most studied chemicals and are currently believed to be of greatest health concern [18]. Table 1 shows that fuels have historically contained large fractions of toxic and carcinogenic chemicals. In many countries, lead and MTBE are no longer used. Benzene levels in gasoline are currently much lower in most countries (e.g., on average 0.62 % by volume in the USA), though the chronic health effects of benzene and other BTEX chemicals at relevant exposure levels are not well understood.

Chronic Release and Environmental Transport of Contaminants from Fuel

At gas stations, fuel can be released in both liquid and vapor phases during delivery, storage, and dispensing. Direct vapor release is usually associated with atmospheric pollution, while liquid spillage is commonly associated with soil and groundwater contamination. However, spilled liquid fuel also evaporates into the atmosphere. Hypothetically, hydrocarbon vapors can also condense back into liquid form; however, this appears to be unlikely due to quick dilution in a typically turbulent atmosphere. Figure 1 depicts how releases of unburned fuel contaminate the atmospheric, subsurface, and surface water environments (omitting LUST and leaky piping as well as marine gas stations which may release fuel directly to surface water).

Liquid Fuel Spills

Liquid fuel spills at the nozzle have received less attention than liquid releases due to LUSTs. These fuel spills occur when the dispensing nozzle is moved from the dispensing station to the vehicle tank and vice versa, when the automatic shutoff valve fails, due to spitback from the vehicle tank after the shutoff has been activated, and when the customer tops off the tank.

Table 1 Historical content of non-negligible amounts of toxic and carcinogenic chemicals in fuel

Chemical of concern	Fraction	Health effects
Benzene	Up to 5 % [75]	Carcinogenic [2]
Lead	Up to 2 g per gallon [76]	Central nervous system [12]
MTBE	Up to 15 % [77]	Potential human carcinogen [78]

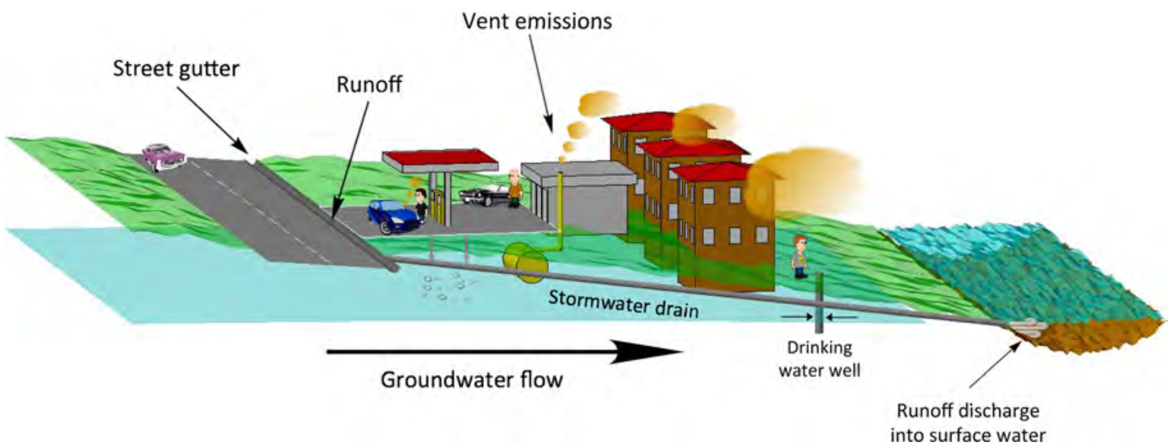

Fig. 1 Gas stations are embedded into the natural environment and can consequently release pollutants to the atmosphere, the subsurface including soil and groundwater, and surface water

In a study quantifying fuel spill frequencies and amounts at gas stations in California, about 6 L of gasoline was spilled per 16,200 gallons of gasoline dispensed at gas stations without stage II vapor recovery compared to 3.6 L at gas stations per 14,043 gallons of gasoline dispensed at gas stations with stage II vapor recovery (at the nozzle) [19]. This would mean that about 0.007 and 0.01 % of dispensed gasoline are spilled in liquid form during vehicle refueling at gas station with and without stage II recovery (numbers calculated using the assumed fuel density of 6.2 pounds/gallon). On the other hand, a study sponsored by the American Petroleum Institute found that more spills occurred at gas stations with stage II recovery [20].

We have recently performed laboratory experiments to examine the fate of liquid spill droplets. Following our previous protocol [21•], we spilled fuel droplets onto small concrete samples and measured the mass added to the concrete as a function of time. This added mass is the sum of the masses of the sessile fuel droplet and the infiltrated fuel. Figure 2 shows results for diesel and gasoline. After a certain period of time, the sessile droplet vanishes and the measured mass levels off. The remaining mass represents the infiltrated portion. The evaporated mass can be obtained by subtracting the infiltrated mass from the initial droplet mass m_0. Evaporation is greater for gasoline, while infiltration is greater for diesel spills. This is because gasoline is more volatile than diesel. Diesel has therefore a higher potential for soil contamination because of the higher infiltrated mass.

Spilled fuel may move downward in liquid or vapor phase and potentially reach the groundwater table. The physical mechanisms that govern subsurface movement of spilled fuel are the same as for fuel released due to LUST, except that spilled fuel must first penetrate relatively impermeable pavement underneath fuel-dispensing stations. Gasoline and diesel will not penetrate the groundwater table as a liquid, because they have densities lower than that of water. Released fuel may also evaporate within the sediment, and a portion of it will move downward as a vapor and potentially reach the groundwater table [22]. Whether the fuel reaches groundwater in liquid or vapor form, the fuel will then partition into groundwater and become a dissolved chemical that is carried away by molecular diffusion and groundwater flow and associated hydrodynamic dispersion [23]. Therefore, the spills can contaminate downstream drinking water wells [24]. Biodegradation can decrease contaminant concentrations significantly; however, its efficiency depends on many factors including the chemical composition of the fuel and the presence of suitable microbial species that can metabolize a given contaminant, bioavailability, and electron acceptor availability [25]. Partitioning of the contaminant into other phases will cause

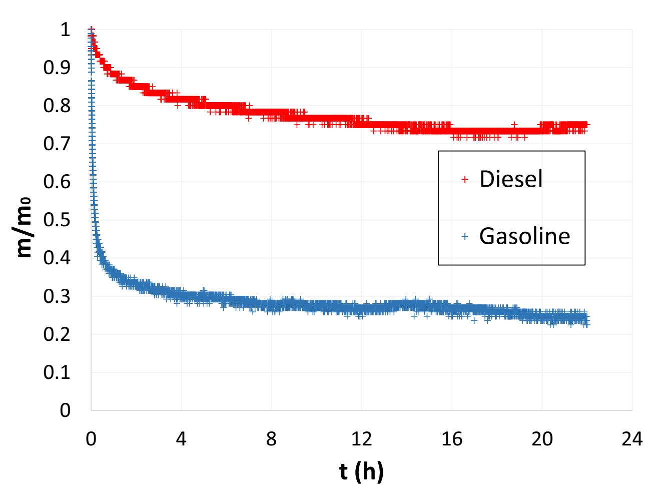

Fig. 2 Results from laboratory experiments, in which we spilled a mass m_0=1 g of diesel or gasoline onto concrete samples. The measured mass m represents the masses of the sessile droplet and infiltrated liquid

retarded transport of the contaminant within groundwater. For instance, hydrophobic contaminants such as benzene tend to sorb to the sediment. For this reason, large-scale contamination of aquifers and associated adverse health effects due to the ingestion of contaminated drinking water from these aquifers are often considered a lesser concern for hydrophobic contaminants [16].

Stocking et al. [26] evaluated the potential of groundwater contamination due to small one-time releases of liquid gasoline. In a case study, they assumed a spill volume much bigger than the ones typically measured by the study of gas stations in California [19], i.e., 0.5 L, and they concluded the risk to groundwater to be small. This analysis, however, did not include consideration of a key mechanism for fuel spillage; namely, that much smaller droplets are typically released during vehicle refueling [19]. To address this question, Hilpert and Breysse [21•] calculated cumulative spill volumes due to repeated small spillages that occur at gasoline-dispensing facilities and estimated that a gas station selling about 400,000 L of gasoline per month would spill at least 150 L each year. They also developed a model that shows that the fraction of spilled gasoline that infiltrates into the pavement increases as the droplet size decreases. Therefore, repeated small spills could be of greater concern for groundwater contamination than an instantaneous release of the cumulative spill volume; thus, a risk to groundwater may not be as small as previously estimated.

Laboratory experiments and modeling have shown that gasoline from small-volume spills can infiltrate into the concrete that usually covers the ground underneath gasoline-dispensing stations—despite the low permeability of concrete and the high vapor pressure of gasoline [21•]. It is unlikely that liquid fuel fully penetrates a concrete slab to contaminate the underlying natural subsurface due to the low permeability of concrete [27], although preferential pathways for fluid flow such as cracks and faulty joints between concrete slabs can allow for such liquid penetration. It has been hypothesized that evaporation of infiltrated gasoline and subsequent downward migration of the vapor through the concrete may lead to contamination of underlying sediment and groundwater [21•]. Consistent with these two proposed pathways of subsurface contamination, soil/sediment underneath concrete pads of a gas station in Maryland was contaminated by diesel oil and gasoline (leaky piping could have also contributed to the contamination) [28].

Runoff water that flows over pavement can also get contaminated with hydrocarbons spilled onto the pavement [29–31], and such contamination has specifically been linked to gas stations [32–34]. If a spill occurs while runoff occurs, the hydrocarbon can be expected to float on top of the water sheet, because gasoline, diesel oil, and lubricants are typically less dense than water (light non-aqueous phase liquids or LNAPLs). While runoff water is not directly ingested, it is funneled into the stormwater drainage system, and may be released to natural water bodies, often without treatment. Whereas volatilization decreases contaminant levels in the stormwater within hours depending on the exact environmental conditions [35], and biodegradation will further decrease levels, significantly contaminated stormwater might be released to natural water bodies if they are close by. Finally, fuel spilled at marine gas stations may directly enter natural water bodies.

Vapor Fuel Releases

Fuel evaporative losses have received more attention than liquid fuel spills (even though they are related) [6, 36]. These losses are related to the fact that the headspace above liquid fuel in vehicle and storage tanks tends to approach thermodynamic equilibrium with the liquid. Consequently, almost saturated gasoline vapors can be released to the atmosphere when tanks are refueled, unless a suitable vapor recovery system is in place. Since saturated gasoline vapors have a density that is three to four times larger than the one of air, i.e., 4 kg/m^3, and the density of liquid gasoline is about 720 kg/m^3 [37], about 0.5 % of liquid gasoline dispensed to a tank is released to the atmosphere if the entire headspace is in equilibrium with the liquid fuel. This is true for any type of tank, whether it is a vehicle tank, a canister, an underground storage tank (UST), or an above-storage tank. The percentage loss is less if a tank received clean air relatively recently, e.g., when the fuel level in a storage tank drops because of gasoline-fuel dispensing.

It is important to note that vapor recovery at the nozzle can cause vapor releases at the storage tank, because vapors recovered at the nozzle are typically directed into the storage tank. The storage tank, in turn, can “breathe” and potentially release recovered vapors immediately or at a later time. A tank sucks in relatively uncontaminated air as the liquid fuel level drops in the tank due to vehicle refueling, and it releases vapors through the vent pipe into the atmosphere if the gas pressure increases and exceeds the cracking pressure of the pressure/vacuum valve, when fuel evaporates into unequilibrated gas in the headspace.

As discussed in the “Liquid Fuel Spills” section above, we note that liquid spills also contribute to air pollution because spilled droplets form sessile droplets on pavement that can then evaporate into the atmosphere. On concrete, most of spilled gasoline droplets evaporate into the atmosphere (Fig. 2). This, however, does not mean that the small fraction that infiltrates into the concrete is not of concern.

Exposure and Risks to Human Populations

Gas stations exist as part of the built environment and are widely distributed across communities. As a result, they may be surrounded by residential dwellings, businesses, and other buildings such as schools. Operation of gas stations may thus create opportunities for a variety of human populations to be exposed to vapors during station tank filling and vehicle refueling. These human populations can be broadly grouped into three groups: populations exposed occupationally as a result of employment in various capacities at the service station; those exposed as customers engaging in vehicle refueling; and those passively exposed either by residing, attending school, or working near the refueling station. The exposures to benzene and other components of refueling vapors and spills experienced by these populations vary based on a number of factors, including the size and capacity of the refueling station, spatial variation in pollutant concentrations in ambient air, climate, meteorological conditions, time spent at varying locations of the service station, changing on-site activity patterns, physiological characteristics, and the use of vapor recovery and other pollution prevention technologies.

Employees at service stations (such as pump attendants, on-site mechanics, and garage workers) are among those with greatest exposure to benzene originating from gas stations [3]. These receptors spend the most time on site (potentially reflecting approximately 40 h per week, for decades) and intermittently spend time where vapors from the pump are at their highest concentrations, with benzene concentrations measuring between 30 and 230 ppb in the breathing zone [38–40]. Gas station patrons can also be exposed to vapors when refueling. Compared to station employees, their exposures are brief and transient. A Finnish study reported a median time spent refueling of approximately 1 min, whereas 3 min was the median duration in the USA [41, 42]. The same US study reported an average benzene personal exposure concentration at the pump of 910 ppb, with the strongest predictors of benzene levels being fuel octane grade, duration of exposure, and season [42].

Those occupying residences, businesses, and other structures neighboring gas stations can also be exposed to fuel vapors originating in the gas station, though typically at lower concentrations than those measured at the pump. While vapor concentrations will drop as the distance from the service station increases, exhaust fumes from waiting customers and fuel delivery trucks can also contribute to vapors in proximity to gas stations. A small number of studies have examined benzene concentrations at the fenceline of the service station and beyond. A study published by the Canadian petroleum industry found average benzene concentrations of 146 and 461 ppb at the gas station property boundary in summer and winter, respectively [43]. A South Korean study examined outdoor and indoor benzene concentrations at numerous residences within 30 m and between 60 and 100 m of gas stations and found median outdoor benzene concentrations of 9.9 and 6.0 μg/m^3 (about 3.1 and 1.9 ppb), respectively. Median indoor concentrations at these locations were higher, reaching 13.1 and 16.5 μg/m^3 (about 4.1 and 5.2 ppb), respectively [44]. Another study found median ambient benzene levels of 1.9 ppb in houses both <50 and >100 m from a service station [45]. Yet, another study [46] found that benzene and other gasoline vapor releases from service stations can be discerned from traffic emissions as far as 75 m from service stations and that the contribution of service stations to ambient benzene is less important in areas of high traffic density. This is because vehicle exhaust is usually the most abundant volatile organic compound (VOC) in urban areas, often followed by gasoline vapor emissions from fuel handling and vehicle operation [47].

Beyond contact with surface-level gasoline vapors, fuel releases may result in other exposure pathways. Soil and groundwater contamination is common at gas stations. Drinking water wells proximate to gas stations, which in rural areas are often the only drinking water source, can become contaminated, potentially exposing well users to benzene and other chemicals [48, 49]. In addition, runoff from rain and other weather events can carry spilled hydrocarbons, which can contaminate surface waters; those using surface waters, either recreationally or for other purposes, may be exposed to these contaminants through dermal contact or incidental ingestion.

In the USA, the Environmental Protection Agency (EPA) regulates releases of benzene under the Clean Air Act as a hazardous air pollutant, and benzene is listed as number 6 on the 2005 priority list of hazardous substances under the Comprehensive Environmental Response, Compensation, and Liability Act and any release greater than 10 pounds triggers a reporting requirement. Different quantitative toxicity metrics exist for benzene inhalation. The EPA Integrated Risk Information System (IRIS) has published a reference concentration of 0.03 mg/m^3 (about 9.4 ppb), corresponding to decreased lymphocyte counts [50], whereas the NIOSH recommended exposure limit (REL) is a time-weighted average concentration (for up to a 10-hour workday during a 40-hour workweek) of 0.319 mg/m^3 (about 100 ppb) [51].

While research attention has been paid to measurement of gasoline vapor constituent concentrations in air at and near service stations, less is known about the health consequences faced by those that are exposed to gasoline vapors. Of the limited literature examining these exposures, service station workers have received the greatest attention, and exposure is often assessed as a function of job title, rather than specific measurements of vapor constituent concentrations. An older study looking broadly at leukemia incidence in Portland, Oregon, found that gas station workers were at significantly increased risk for lymphocytic leukemia [52]. A proportionate mortality ratio analysis of all deaths recorded in New Hampshire among white men from 1975 to 1985 found elevated leukemia mortality in service station workers and auto mechanics [53]. The type of leukemia was not specified. An Italian occupational cohort study of refilling attendants that examined risks among workers at smaller gas stations reported non-significant increases in mortality for non-Hodgkin's lymphoma and significantly elevated mortality for esophageal cancer in men, as well as increased brain cancer mortality in both sexes [54]. A different cohort of 19,000 service station workers in Denmark, Norway, Sweden, and Finland examined an array of cancer end points and found increased incidence for multiple sites (nasal, kidney, pharyngeal, laryngeal, and lung) among workers estimated to be occupationally exposed to benzene in the range of 0.5–1 μg/m^3 (0.16 - 0.31 ppb). Non-significant increased incidence was found for acute myeloid leukemia in men and for leukemia different from acute myeloid leukemia and chronic lymphocytic leukemia in women [55]. A case–control study of multiple occupations including subjects from the USA and Canada found significant increases in rates of total leukemia and acute myeloid leukemia but not acute lymphocytic leukemia in gas station attendants [56]. A 2015 review of studies examining potential relationships between benzene exposures and hematopoietic and lymphatic cancers among vehicle mechanics yielded inconclusive results, although it suggested that if an effect was to exist, it would be small and difficult to rigorously ascertain with existing epidemiologic methods [57].

The health consequences of nearby residents of gas stations have not been studied. However, it is known that contaminated groundwater can affect large numbers of people if the groundwater is used as drinking water, as was the case in Camp Lejeune (North Carolina, USA) where thousands were exposed to a range of chemicals including gasoline released from LUSTs [58]. A study of Pennsylvania residents residing in close proximity to a large gasoline spill from a LUST found evidence of increased leukemia risks [49, 59••]. The health consequences of chronic fuel releases at gas stations that can, for example, occur due to ingestion of contaminated groundwater, fuel vapor intrusion from contaminated soil and groundwater into dwellings [60], and atmospheric vapor releases during fuel transfer and storage have not been studied. While limited measurements of ambient concentrations of vapor constituents in communities were identified, literature searches did not identify studies of the health consequences of inhalation exposures to gasoline vapors among community residents [61].

Pollution Prevention

Pollution prevention technologies have been developed that can efficiently reduce the releases of unburned fuel to the environment that routinely occur during fuel storage and transfer (see Fig. 3):

1. Stage I vapor recovery collects vapors that would be expelled from USTs during fuel delivery [62]. Without stage I vapor recovery, about 80 kg of gasoline vapor would be released from a 40 m^3 UST if one assumes a saturated vapor density of 4 kg/m^3 [37] and vapors in the headspace

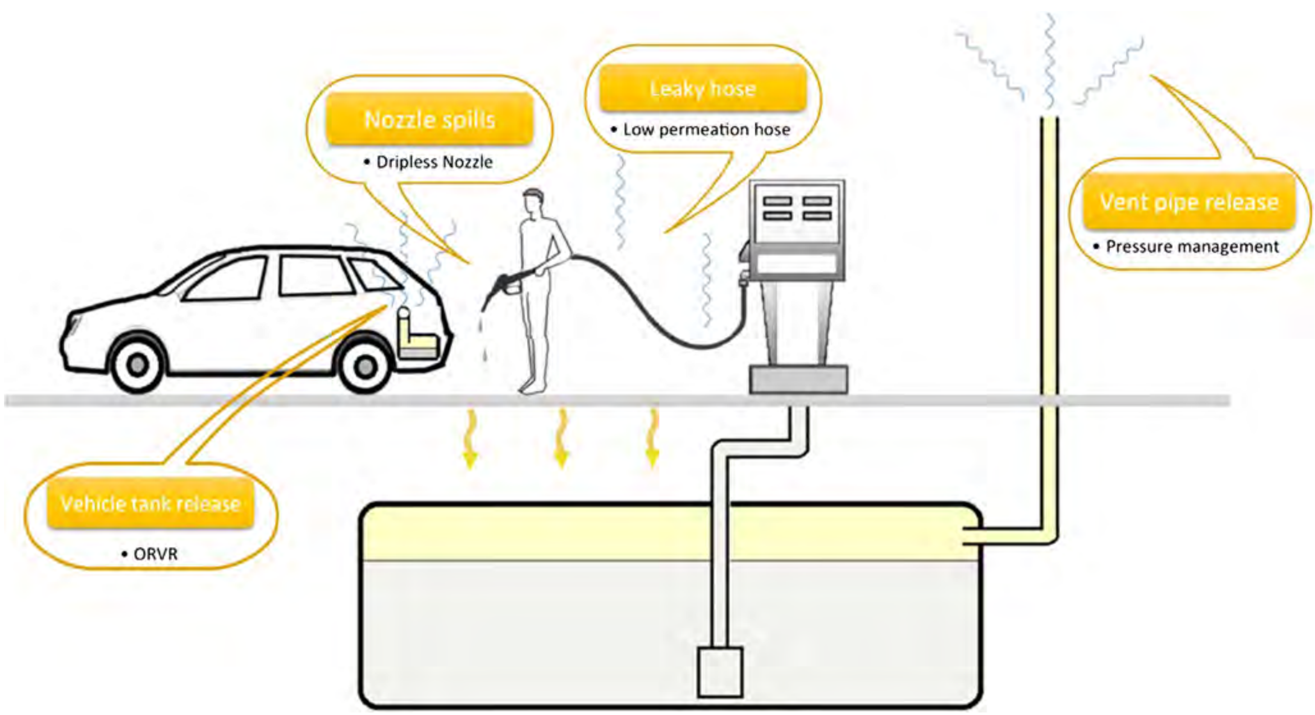

Fig. 3 There are several sources of chronic release of unburned fuel at gas stations that occur due to fuel storage and dispensing: vapor release through the vent pipe of the storage tank, vapor release from the vehicle tank during refueling, leaky dispensing hoses, liquid spills during vehicle refueling, and vapor emissions through evaporation of this spilled fuel. As indicated, suitable pollution prevention technology can minimize the releases. Onboard refueling vapor recovery (ORVR)

to be at half saturation. Stage I vapor recovery can thus prevent substantial fuel vapor releases that would occur within a short period of time. Such releases might expose tanker truck drivers and persons in the proximity of a gas station to significant doses of fuel vapors. Stage I vapor recovery is accomplished by establishing a closed loop between the UST and the tanker truck. Through a fuel delivery hose, liquid fuel is pumped into the UST, while a vapor recovery hose directs vapors displaced from the UST into the headspace of the tanker truck. Stage I vapor recovery is currently required for high-throughput gas stations in all states in the USA and in most countries.

2. Stage II vapor recovery technology can efficiently collect vapors expelled from vehicle tanks during refueling, thereby minimizing personal exposure of customers and workers to fuel vapors during dispensing of gas [63]. Recovered vapors are directed into the UST. Two technologies for stage II vapor recovery have been developed, the vaccum-assist method and the balance method. In the vacuum-assist method, contaminant-laden air is actively removed/pumped from the nozzle into the UST. In the balance method, displaced vapors are passively withdrawn by connecting the vapor recovery hose to the inlet of the vehicle tank via an airtight seal. The pressure increase in the headspace of the vehicle tank provides a driving force that seeks to push the vapors into the storage tank. Stage II vapor recovery has been required in many states of the USA and in other countries, although there is currently an effort to decommission stage II vapor recovery (see below).
3. Technology development at the hose and nozzle level can also contribute to reduced fuel releases. Low-permeation hoses, for instance, limit the release of gasoline vapors through the wall of the refueling hoses [64]. Dripless nozzles have been developed to minimize liquid spills that occur when the nozzle is moved between the fill pipe and the dispensing unit.
4. Passenger vehicles and trucks can be equipped with on-board refueling vapor recovery (ORVR) systems which direct vapors that, during vehicle refueling, would be released to the atmosphere into an activated carbon-filled canister in the vehicle [65, 66]. Collected vapors are later reintroduced into the vehicle's fuel system. However, canisters, motorcycles, and boats are not equipped with ORVR.
5. Impermeable liners underneath the concrete pads can reduce the risk of soil and groundwater contamination once environmental fuel releases, in liquid or vapor phase, have occurred. However, this technology might eventually result in air pollution, because liquid fuel that is hindered from moving downward in the concrete pad will tend to saturate the pavement and eventually evaporate into the atmosphere.
6. Finally, unburned fuel vapor can be released from an UST when the tank pressure exceeds the cracking pressure of the pressure/vacuum valve and it can be prevented by two pressure management techniques, burning or separation of air and fuel vapors. Released air/fuel vapors can be burned, however, which results in the release of combustion-related pollutants into the atmosphere. Alternatively, a semi-permeable membrane can be used to separate the air from the fuel vapors. Depressurization of the tank is then achieved by releasing the relatively clean air through the pressure/vacuum valve to the atmosphere.

When it comes to evaluating the efficiency of vapor recovery during liquid transfer between tanks, it is of upmost importance to consider potential releases from all tanks; they form a system. Otherwise, the overall efficiency of stage II vapor recovery cannot be understood. For instance, stage II vapor recovery based on the vacuum-assist method can negatively interfere with ORVR. In that case, no vapors are released from the vehicle tank and the stage II pump draws relatively clean air from the atmosphere into the storage tank. In the UST, this air will become saturated with fuel vapors that evaporate from the stored fuel. This results in pressurization of the UST and release of contaminant-laden air if the tank pressure exceeds the cracking pressure of the pressure/vacuum valve of the UST. This might occur immediately or at a later point in time. However, there are stage II systems that do not negatively interfere with ORVR including the balance method.

Estimates for the efficiency of pollution technologies are usually provided by the manufacturers. However, adoption of these technologies by gas station owners usually relies on the certification and quantification of efficiencies by independent parties. In the USA, the California Air Resources Board and EPA typically assume this role [36]. Consultants and environmental agencies have used these estimates to determine current releases of unburned fuel to the environment and to evaluate the effects of pollution prevention technology [67].

While many studies have found health benefits from pollution prevention technology intended to minimize chronic gasoline spills, these studies typically do not quantify overall financial benefits and costs. Instead, only equipment and maintenance cost are typically considered [68]. Adopting the new equipment can reduce fuel losses and reduce environmental cost and health risks. However, this new equipment comes with non-trivial upfront costs. It is therefore a concern that the related policy-making process of chronic fuel spills relies only on non-comprehensive cost estimates. Studies are needed that account for health care cost due to released pollutants and energy-saving benefits due to pollution prevention. Such econometric studies have, for example, been performed in the context of pollutant emissions from coal-fired power plant and commercial real estate development [69••, 70]. At times, there is also the perception that pollution prevention costs are only carried by the specific industry [71]. Adoption of the environmentally friendly technology could be slow when the firms have long equipment replacement cycles or when the firms do not have sufficient information to evaluate whether or not a switch to an environmentally friendly technology is in their private interests. It is, however, not clear that this apparent investment, in the form of prevention cost, might also be partly shouldered by customers and that this apparent cost might actually (at least in the long run) be beneficial to customers, gas station workers, nearby residents, and other populations that spend significant amounts of times in the proximity of gas stations (e.g., school children in nearby schools). Policy intervention is often expected to expedite the adoption of such environmental friendly technologies, in order to reduce the difference in the private and social values of adoption.

Efforts are currently underway that could potentially allow decommissioning stage II vapor recovery in the USA due to the widespread use of ORVR in the motor vehicle fleet [68]. However, the remaining legacy fleet without ORVR and all motorcycles and boats (lacking ORVR) can produce significant emissions during vehicle refueling, emissions that could be avoided by stage II vapor recovery. For the State of Maryland, it has been estimated that fuel consumption of non-ORVR-equipped vehicles was about 10 % in 2015 (Table 4 in [67]). These emissions can result in direct hydrocarbon exposures among vehicle owners during vehicle refueling as well as in passive exposure of other populations. A comprehensive cost analysis of the decommissioning of stage II recovery represents an opportunity to inform policy makers on their recommendation with regards to stage II recovery.

Conclusions

Even if only a small fraction of unburned fuel is lost during vehicle refueling and fuel storage, the cumulative release of fuel to the environment can be large if large total amounts of fuel are dispensed at gas stations. For instance, about 0.01 % of fuel can be spilled during the refueling process and up to about 0.5 % can be lost in vapor form if equilibrated gasoline vapors are released from a tank to the atmosphere during refueling (worst-case scenario). For a medium-size gas station, which sells 400,000 L of gasoline per month, this results in 480 L of spilled gasoline and in 24,000 L of liquid gasoline that is anually released in vapor form to the environment. Even though dilution can reduce concentrations of released contamination, research is needed to assess whether such releases represent an environmental health concern.

The potential for pollution prevention, moreover, is substantial. Technology has already been developed and partially employed that can efficiently decrease vapor losses and liquid spills. Particularly, when it comes to vapor losses, it is crucial to consider not only vapor recovery at the vehicle tank/nozzle but also at the storage tank, since vapors recovered at the nozzle are directed into the storage tank, from which they might be potentially released. While California has implemented the strictest regulations when it comes to preventing chronic hydrocarbon releases at gas stations, other highly industrialized states and nations do not employ the same standards for different reasons. For instance, pressure/vacuum valves on vent pipes of fuel storage tanks are not common in Canada, because they might freeze in the wintertime, potentially causing a tank implosion [6].

Relatively little research has been done on potential soil and groundwater contamination due to chronic releases of liquid fuel during vehicle refueling. Unlike catastrophic releases, such as LUST, chronic spills are not reported. Limited field investigations suggest that spilled fuel may penetrate concrete underneath dispensing pads to contaminate underlying sediment. However, it is possible that such soil contamination occurs routinely over the life span of a gas station and that this contamination pathway is masked or erroneously explained by leaks in the piping from the USTs to the dispensers. Overall, large-scale soil and groundwater contamination by fuel appears to be a lesser problem, because many of the toxic compounds in fuel are hydrophobic (including BTEX) and can therefore be expected not to travel too far in groundwater. However, customers, gas station workers, and nearby residents may get exposed to the hydrocarbons if groundwater is used as a drinking water supply or if fuel vapor intrusion in dwellings occurs.

Health effects of living near gas stations are not well understood. Adverse health impacts may be expected to be higher in metropolitan areas that are densely populated. Particularly affected are residents nearby gas stations who spend significant amounts of time at home as compared to those who leave their home for work because of the longer period of exposure. Similarly affected are individuals who spend time close to a gas station, e.g., in close by businesses or in the gas station itself. Of particular concern are children who, for example, live nearby, play nearby, or attend nearby schools, because children are more vulnerable to hydrocarbon exposure [72].

Potential future changes in fuel composition might pose new environmental health challenges as there is a history of adding even large amounts of toxic substances to fuel (Table 1). Changes in fuel composition could occur due to an increasing usage of biofuels, or to comply with air quality standards, which might also change over time. Chemicals newly added to fuel or changes in chemical concentrations can have unforeseen ramifications. One could argue that future fuel composition changes will be performed with more care; however, it was only in the 1990s, decades after the Safe Drinking Water Act (SDWA) was passed in 1974, that MTBE was added to gasoline without critically evaluating its transport behavior in groundwater and toxicity, a mistake which nowadays is considered avoidable [73]. Interestingly, ethanol, which has largely replaced MTBE, can inhibit biodegradation of BTEX, which is not the case for MTBE [74]. Given the complexities of chemical fate and transport in the environment and the potential for insufficient toxicity testing, using appropriate pollution prevention technology that minimizes release of unburned chemicals with known and unknown adverse health effects during fuel storage and transfer seems a wise, long-term, and cost effective idea given ever-changing fuel compositions.

Finally, employing efficient pollution prevention technology might be economically advantageous. The evaluation of economic benefits of pollution prevention technology needs to account not only for the cost of implementation and maintenance of such technology but also for public health burdens due to released pollutants and energy-saving benefits due to valuable hydrocarbons not wastefully released to the environment.

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Compliance with Ethics Guidelines

Conflict of Interest Markus Hilpert, Bernat Adria Mora, Jian Ni, Ana Rule, and Keeve Nachman declare that they have no conflict of interest.

Human and Animal Rights and Informed Consent This article does not contain any studies with human or animal subjects performed by any of the authors.

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2019 Study

Vent pipe emissions from storage tanks at gas stations: Implications for setback distances

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Vent pipe emissions from storage tanks at gas stations: Implications for setback distances

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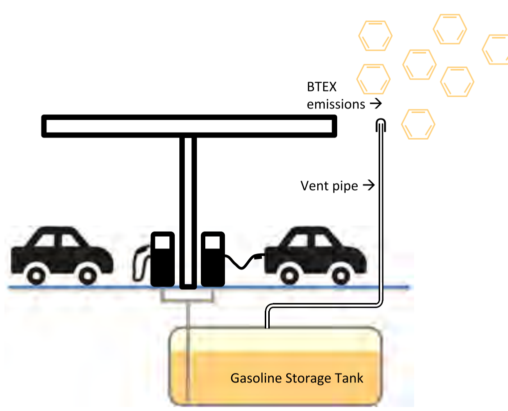
HIGHLIGHTS

- At gas stations, fuel vapors are released from storage tanks through vent pipes.
- We measured vent pipe flow rates and tank pressure at high temporal resolution.
- Vent emission factors were >10 times higher than previous estimates.
- Modeling was used to examine exceedance of benzene short-term exposure limits.

GRAPHICAL ABSTRACT



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ABSTRACT

At gas stations, fuel vapors are released into the atmosphere from storage tanks through vent pipes. Little is known about when releases occur, their magnitude, and their potential health consequences. Our goals were to quantify vent pipe releases and examine exceedance of short-term exposure limits to benzene around gas stations. At two US gas stations, we measured volumetric vent pipe flow rates and pressure in the storage tank headspace at high temporal resolution for approximately three weeks. Based on the measured vent emission and meteorological data, we performed air dispersion modeling to obtain hourly atmospheric benzene levels. For the two gas stations, average vent emission factors were 0.17 and 0.21 kg of gasoline per 1000 L dispensed. Modeling suggests that at one gas station, a 1-hour Reference Exposure Level (REL) for benzene for the general population (8 ppb) was exceeded only closer than 50 m from the station's center. At the other gas station, the REL was exceeded on two different days and up to 160 m from the center, likely due to non-compliant bulk fuel deliveries. A minimum risk level for intermediate duration (>14–364 days) benzene exposure (6 ppb) was exceeded at the elevation of the vent pipe opening up to 7 and 8 m from the two gas stations. Recorded vent emission factors were >10 times higher than estimates used to derive setback distances for gas stations. Setback distances should be revisited to address temporal variability and pollution controls in vent emissions.

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1. Introduction

In the US, approximately 143 billion gal (541 billion L) of gasoline were dispensed in 2016 at gas stations (EIA, 2017) resulting in release of unburned fuel to the environment in the form of vapor or liquid (Hilpert et al., 2015). This is a public health concern, as unburned fuel chemicals such as benzene, toluene, ethyl-benzene, and xylenes (BTEX) are harmful to humans (ATSDR, 2004). Benzene is of special concern because it is causally associated with different types of cancer (IARC, 2012). Truck drivers delivering gasoline and workers dispensing fuel have among the highest exposures to fuel releases (IARC, 2012). However, people living near or working in retail at gas stations, and children in schools and on playgrounds can also be exposed, with distance to the gas stations significantly affecting exposure levels (Terres et al., 2010; Jo & Oh, 2001; Jo & Moon, 1999; Hajizadeh et al., 2018). A meta-analysis (Infante, 2017) of three case-control studies (Steffen et al., 2004; Brosselin et al., 2009; Harrison et al., 1999) suggests that childhood leukemia is associated with residential proximity to gas stations.

Sources of unburned fuel releases at gas stations include leaks from storage tanks, accidental spills from the nozzles of gas dispensers (Hilpert & Breysse, 2014; Adria-Mora & Hilpert, 2017; Morgester et al., 1992), fugitive vapor emissions through leaky pipes and fittings, vehicle tank vapor releases when refueling, and leaky hoses, all of which can contribute to subsurface and air pollution (Hilpert et al., 2015). Routine fuel releases also occur through vent pipes of fuel storage tanks but are less noticeable because the pipes are typically tall, e.g., 4 m. These vent pipes are put in place to equilibrate pressures in the tanks and can be located as close as a few meters from residential buildings in dense urban settings (Fig. 1).

Unburned fuel can be released from storage tanks into the environment through "working" and "breathing" losses (Yerushalmi & Rastan, 2014). A working loss occurs when liquid is pumped into or out of a tank. For a storage tank, this can happen when it is refilled from a tanker truck or when fuel is dispensed to refuel vehicles (Statistics Canada, 2009) if the pressure in the storage tank exceeds the relief pressure of the pressure/vacuum (P/V) valve (EPA, 2008). P/V valve threshold pressures are typically set to around +3 and −8 in. of water column (iwc) (7.5 and −20 hPa). However, P/V valves are not always used, particularly in cold climates, as valves may fail under cold weather conditions (Statistics Canada, 2009).

Breathing losses occur when no liquid is pumped into or out of a tank because of vapor expansion and contraction due to temperature and barometric pressure changes or because pressure in the storage tank may increase when fuel in the tank evaporates (Yerushalmi & Rastan, 2014; EPA, 2008). Although delayed or redirected by the P/V valve, breathing emissions can be significant and represent an environmental and health concern (Yerushalmi & Rastan, 2014).

Fig. 1. The three vent pipes (enclosed by the red ellipse) on the right side of the convenience store of a gas station are <10 m away from the residential building. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Stage I vapor recovery systems, put in place to prevent working losses while delivering fuel to a station, collect the vapors displaced while loading a storage tank, redirecting them into the delivery truck. Stage II vapor recovery systems minimize working losses while delivering gas from the storage tank to the customer's car. During Stage II vapor recovery, gasoline vapors can be released through the vent pipe, if the sum of the flow rates of the returned volume and of the fuel evaporating within the storage tank is greater than the volume of liquid gasoline dispensed (Statistics Canada, 2009). We refer to this scenario as pressure while dispensing (PWD). In theory, a properly designed Stage II vapor recovery system should not have working losses, although in practice this is not typically the case (McEntire, 2000).

Regulations on setback distances for gas stations are based on lifetime cancer risk estimates. Several studies have assessed benzene cancer risk near gas stations (Atabi & Mirzahosseini, 2013; Correa et al., 2012; Cruz et al., 2007; Edokpolo et al., 2015; Edokpolo et al., 2014; Karakitsios et al., 2007). Based on cancer risk estimations, the California Air Resources Board (CARB) recommended that schools, day cares, and other sensitive land uses should not be located within 300 ft. (91 m) of a large gas station (defined as a facility with an annual sales volume of 3.6 million gal = 13.6 million L or greater) (CalEPA/CARB, 2005). This CARB recommendation has not been adopted by all US states, and within states setback distances can depend on local government. Notably, CARB regulations do not account for short term exposure limits and health effects. An important limitation of existing regulations is the use of average gasoline emission rates estimated in the 90s that do not consider excursions (CAPCOA, 1997).

The main objective of this study is to evaluate fuel vapor releases through vent pipes of storage tanks at gas stations based on vent emission measurements conducted at two gas stations in the US in 2009 and 2015, including the characterization of excursions at a high temporal resolution (~minutes) and meteorological conditions at an hourly temporal resolution. In addition, we performed hourly simulations of atmospheric transport of emitted fuel vapors to inform regulations on setback distances between gas stations and adjacent sensitive land uses by comparing modeled benzene concentrations to four 60-min benzene exposure limits: an acute Reference Exposure Level (REL) for infrequent (once per month or less) exposure (WHO, 2010) and Emergency Response Planning Guidelines ERPG-1, ERPG-2 and ERPG-3 (AIHA, 2016). Finally we compared simulated benzene levels to a Minimal Risk Level (MRL) for benzene for intermediate exposure duration (14 to 364 days) (ATSDR, 2018) because that duration window includes our duration of data collection. See Table 1 for the various benzene exposure limits and issuing agencies.

2. Methods

Although we provide SI unit conversions, we report some measures in English engineering units (ft, gal, and lb) as regulatory agencies such as CARB use these units.

2.1. Sites

Data for this study were obtained from vent release measurements conducted at two gas stations as part of technical assistance to the gas stations to quantify fuel vapor losses through the vent pipes of their storage tanks. A motivation for conducting the measurements was to perform a cost-benefit analysis to compare the economic losses due to the lost fuel versus the cost of technologies that reduce the emissions. The exact location of the two gas stations is not revealed for confidentiality reasons. The gas station managers and staff who authorized the

Table 1
Benzene exposure limits, to which we compared simulation results. For unit conversion, we assumed a temperature of 25 °C, i.e., 1 ppm = 3194 μg/m^3 (CAPCOA, 1997).

Agency	Name	Value (ppb)	Value (μg/m^3)	Exposure duration
California Office of Environmental Health Hazard Assessment (OEHHA)	REL	8	26	1 h
American Industrial Hygiene Association (AIHA)	ERPG-1	50	159,700	1 h
AIHA	ERPG-2	150	479,100	1 h
AIHA	ERPG-3	1000	3,194,000	1 h
Agency for Toxic Substances and Disease Registry (ATSDR)	MRL	6	19	14 to 364 days

ERPG = Emergency Response Planning Guidelines. The primary focus of ERPGs is to provide guidelines for short-term exposures to airborne concentrations of acutely toxic, high-priority chemicals.

collection and analysis of these data have not been involved in the current manuscript.

The first gas station, "GS-MW," was located in the US Midwest and is a 24-hour operation. The study was conducted from December 2014 to January 2015 for 20 full days, and fuel sales $\dot{V}_{sales}$ were about 450,000 gal (1.7 million L) per month. Fuel deliveries to the gas station usually took place during the nighttime. The second gas station, "GS-NW," was located on the US Northwest coast and closed at night. Hours of operation were between 6:00 am and 9:30 pm on weekdays and between 7 am and 7 pm on weekends. That study was conducted in October 2009 for 18 full days, and fuel sales were $\dot{V}_{sales}$ ~700,000 gal (2.6 million L) per month.

Both gas stations are considered to be high-volume, because they dispense >3.6 million gal of gasoline (both regular and premium) per year (CalEPA/CARB, 2005), and fuel was stored in underground storage tanks (USTs), which is typical in the US. Both gas stations had Stage II vapor recovery installed using the vacuum-assist method. In that method, gasoline vapors, which would be ejected into the atmosphere as a working loss during refueling of customer vehicle tanks, are collected at the vehicle/nozzle interface by a vacuum pump. The recovered vapors are then directed via a coaxial hose back into the combined storage tank ullage (head space) of the gas station. Stage I vapor recovery was also used at both gas stations during fuel deliveries. Both sites had a 3-inch diameter (7.5 cm) single above-grade vent pipe with below-grade manifold that connected the vent lines from several USTs; the cracking pressures of the P/V valves were set to +3 and −8 iwc (+7.5 and −20 hPa).

2.2. Vent emission measurements

To quantify evaporative fuel releases through the vent pipe of a storage tank, the volumetric flow of the mixture of gasoline vapor and air was measured in the vent pipe. A dry gas diaphragm flow meter (American Meter Company, Model AC-250) was used. For each cubic foot (28 L) of gas flowing through the meter, a digital pulse was generated. Every minute, the number of pulses was read out and stored together with date and time on a data logger. Gas flow meters were obtained from a distributor calibrated and equipped with temperature compensation and a pulse meter.

To determine the time-dependent volumetric flow rate $Q(t)$ of the gasoline vapor/air mixture through the vent pipe, the time series of measured flow volumes were integrated over an averaging period (15 or 60 min) and divided by the duration of that period. I.e., $Q(t)$ is given by the number of pulses registered by the gas flow meter in a time window multiplied by 1 cubic foot and divided by the averaging time. The 15-minute averaging time was chosen to visualize time-dependent data, while the 60-minute averaging time was chosen because air pollution simulations were performed at that resolution.

Gas pressure p in the ullage of the storage tank was measured to assess vent emission patterns. For instance, releases can occur when the pressure exceeds the cracking pressure of the P/V valve in the vent pipe (the dry gas flow meter was fitted with a P/V valve on the outlet). Pressure was measured with a differential pressure sensor (Cerabar PMC 41, Endress + Hauser) every 4 s, and 2-minute average values were stored. The sensor range was scaled from −15 to +15 iwc (−37 to +37 hPa), with a full scale accuracy of 0.20%. We also obtained 15- and 60-minute averaged tank pressure data $p(t)$ where averages represent the means of the 2-minute average pressure measurements taken during each time window.

2.3. Descriptive analysis

For the 60-minute flow rate, we calculated medians and inter quartile ranges (IQRs). To illustrate diurnal fluctuations in vapor emissions, we created box plots for the 60-minute flow rate distribution that occurred during each hour of the day. Spearman correlation coefficients between the time series for pressure and flow rate were calculated to evaluate whether pressure can be used to infer vent emissions.

To estimate the mass flow rate of gasoline $\dot{m}_{gas}$ that is released through the vent pipe in the form of a mixture of gasoline vapors and fresh air, we assumed, following the protocol of a study by the California Air Pollution Control Officers Association (CAPCOA) that assessed risks from fuel emissions from gas station (Appendix D-2 (CAPCOA, 1997)), that the density of gasoline vapors in this mixture is given by $\rho_{gas}^{(v)} = 0.3 \times 65$ lb / 379 ft^3 = 0.824 kg/m^3, i.e., the molar percentages of gasoline and air were 30% and 70%, respectively. Then the volumetric flow rate Q can be converted into a mass flow rate of the vaporized gasoline:

$$\dot{m}_{gas} = \rho_{gas}^{(v)}\ Q \tag{1}$$

To arrive at vent emission factors, we first calculated the mean volumetric flow rate $\overline{Q}$, and then the mean mass flow rate $\overline{\dot{m}}_{gas} = \rho_{gas}^{(v)}\ \overline{Q}$. From the latter, one can calculate the vent emission factor

$$\mathrm{EF}_{vent} = \overline{\dot{m}}_{gas}/\dot{V}_{sales} \tag{2}$$

For EF$_{vent}$, CARB uses units of pounds of emitted gasoline vapors (also called total organic gases (TOG)) per 1000 gal dispensed, or more briefly lb/kgal where kgal stands for kilogallons.

As we were not able to measure benzene levels in the tank ullage, we assumed like the CAPCOA study (Section C) that the density of the mixture of gasoline vapors and fresh air was $\rho_{mix}^{(v)}$ =1.05 lb/ft^3 = 1.682 kg/m^3 and that the emitted gasoline vapor/air mixture contained 0.3% of benzene by weight (CAPCOA, 1997). Therefore, the mass flow rate of benzene through the vent pipe was estimated as follows:

$$\dot{m}_{benz} = 0.003\ \rho_{mix}^{(v)}\ Q \tag{3}$$

2.4. Air pollution modeling

We used the AERMOD Modeling System developed by the US Environmental Protection Agency (EPA) to model the dispersion of benzene vapors released into the environment through vent pipes of fuel storage tanks and from other sources (Cimorelli et al., 2005). AERMOD simulates atmospheric pollutant transport at a 1-hour temporal resolution. 3D polar grids were created with the gas station in the origin and potential receptors at different radial distances (up to 170 m) and angles (10°

increments). The grids were placed at the ground level ($z = 0$ m), in the breathing zone ($z = 2$ m), and at the 2nd floor level ($z = 4$ m) where the vent pipe emissions were assumed to occur. The topography was simplified for modeling purposes consistent with the CAPCOA study (CAPCOA, 1997), i.e., the terrain was assumed to be flat with no buildings present. Vent pipe emissions were modeled as a capped point source. Chemical reactions of benzene were not modeled, as residence times of atmospheric benzene are on the order of hours or even days (ATSDR, 2007), i.e. much longer than the travel time of benzene vapors across the 340-m diameter model domain.

For the period of time when vent emission measurements were made, we obtained meteorological data at a 1-hour temporal resolution that are representative for the geographic locations of the two gas stations. Table SI-1 provides descriptive statistics of that data. The time series were used in AERMOD to model the transport of benzene in the temporally varying turbulent atmosphere. We also used the 1-hour average time series of benzene emission rates (Eq. (3)) as an input into AERMOD.

To evaluate at each grid point whether OEHHA's acute REL or AIHA's ERPG levels were exceeded at least once, we determined maximum 1-hour average benzene concentrations that were simulated for about three weeks. To evaluate how often the OEHHA REL was exceeded at each grid point in the breathing zone, we created plots indicating the number of exceedances and the day when the maximum benzene level was observed.

To facilitate comparison to published benzene measurements around gas stations, we determined for each simulated radial distance from a gas station the mean of the average concentrations simulated for each ten degree increment on the radius around the gas station.

3. Results: vent releases

3.1. Times series of tank pressure and flow rate

Fig. 2 shows the time-series data for the volumetric flow rate Q of the gasoline vapor/air mixture through the vent pipe and tank pressure p that we collected at the two gas stations. At GS-MW, little vapor was typically released in the late night and in the very early morning, while releases were generally much higher during the daytime and evenings, presumably when more fuel was dispensed (Fig. 2a). Occasionally, no vapor releases occurred for several hours. While we do not have access to time of fuel delivery records, field visits indicate that time periods with no releases coincide with fuel deliveries. For instance, fuel delivery likely occurred on January 6 at 7 pm (see Fig. 3a; an amplification of data shown in Fig. 2a). As a result, the UST pressure dropped by about 10 hPa, far below the cracking pressure of the P/V valve. The decreased gas pressure in the ullage increased until the cracking pressure of the P/V valve was reached. A very small vapor release (~2 L/min) was observed briefly on the next day at 2 am. The vapor flow rate becomes relatively large again, ~12 L/min, only after 6 am, i.e., 11 h after fuel delivery.

Fig. 3b amplifies a major vapor release at GS-MW. The UST pressure significantly exceeded the cracking pressure of the P/V valve and rose rapidly up to 37 hPa, which coincides with vapors being released at a high flow rate (15-min average) of about 470 L/min.

At GS-NW, vapor releases followed a quite different pattern (Fig. 2b). Contrary to GS-MW, vapor releases occurred in a cyclical pattern, and tended to be higher in the late night and in the very early morning when the gas station was closed.

3.2. Statistics of vapor emissions

The average volumetric flow rate $\overline{Q}$ through the vent pipe for the entire period of time during which measurements were taken was $\overline{Q} = 7.9$ L/min for GS-MW and $\overline{Q} = 15.4$ L/min for GS-NW, which is consistent with the higher sales volume $\dot{V}_{sales}$ of GS-NW. These emissions consist of a mixture of gasoline vapors and air. Using Eq. (1), the volumetric flow rates were converted into average mass flow rates of gasoline: $\overline{\dot{m}}_{gas} = 0.39$ kg/h for GS-MW and $\overline{\dot{m}}_{gas} = 0.76$ kg/h for GS-NW. Using Eq. (2), we determined a vent emission factor $EF_{vent} = 0.17$ kg per 1000 L = 1.4 lb/kgal for GS-MW and $EF_{vent} = 0.21$ kg per 1000 L = 1.7 lb/kgal for GS-NW.

The medians (IQRs) for the 60-minute averaged flow rate Q (L/min) were 6.1 (1.9, 10.9) for GS-MW and 16.0 (12.7, 18.4) for GS-NW. For GS-MW, the mean is larger than the median, indicating a more skewed distribution of flow rates when compared to GS-NW. Also the first quartile is much lower than the median for GS-MW, indicating that there are periods of time during which little emissions occurred. Conversely, GS-NW was releasing emissions more consistently.

Fig. 4a shows boxplots illustrating the distribution of flow rate Q for each hour of the day at GS-MW. Less vapor was released between 10 pm and 4 am, even though the gas station was in operation, albeit at lower activity levels. The flow rate Q at GS-NW (Fig. 4b) had fewer outliers, and the highest outlier was an order of magnitude lower than the highest one at GS-MW. Emissions were highest between 1 and 3 am, when the gas station was closed.

The Spearman correlation coefficients between tank pressure p and vent flow rate Q were $r = 0.58$ for GS-MW and $r = 0.85$ for GS-NW. Thus, vent releases are moderately and strongly correlated with tank pressure, respectively. Table 2 summarizes statistical properties of vent emissions at the two gas stations.

4. Results: air pollution modeling

4.1. Emission sources and rates

Vent pipe emissions of benzene were modeled at a 1-hour temporal resolution as described in Section 2.4. However, they are not the sole source of gasoline emissions at gas stations. Accidental spills from nozzles regularly occur near the dispensers, "refueling losses" can occur when gasoline vapors are released from the vehicle tank during refueling due to the rising liquid levels in the tanks, fuel vapors are released from permeable dispensing hoses, and "fugitive" or leakage emissions occur with driving force derived from storage tank pressure. In Section A of Supporting material, we detail how these other emission sources were modeled. Table 3 summarizes estimated mean emission rates. Note that the vent pipe losses are much greater than other losses.

4.2. Predicted benzene levels

Fig. 5 shows for both gas stations and at each grid point the maximum 1-hour average benzene concentration observed during the simulated periods in time. Benzene levels depend significantly on elevation within a 50-meter radius around the centers of the gas stations. Close to the centers of the gas stations, benzene levels are higher at the 4-m elevation and at ground level due to vent pipe emissions, which represent the largest emission source (Table 3). Further than 50 m away from the center, the vertical concentration differences become less obvious due to dispersion causing vertical mixing of benzene vapors.

At GS-MW, the 1-hour acute REL of 26 μg/m^3 was exceeded 160 m away from the center of the gas station, at the location ($x = 158$ m, $y = 28$ m) both at ground level and in the breathing zone. At grid points with a distance >50 m from the center of the gas station, the REL was exceeded at most once (Fig. SI-1a). However, the exceedance at different grid points did not occur on the same day (Fig. SI-1b). Within the 20 days during the measurement campaign, exceedances occurred on the 4th and 13th of January.

At GS-NW, the furthest REL exceedance occurred at 50 m from the center of the gas station at the grid point ($x = -38$ m, $y = 32$ m) as

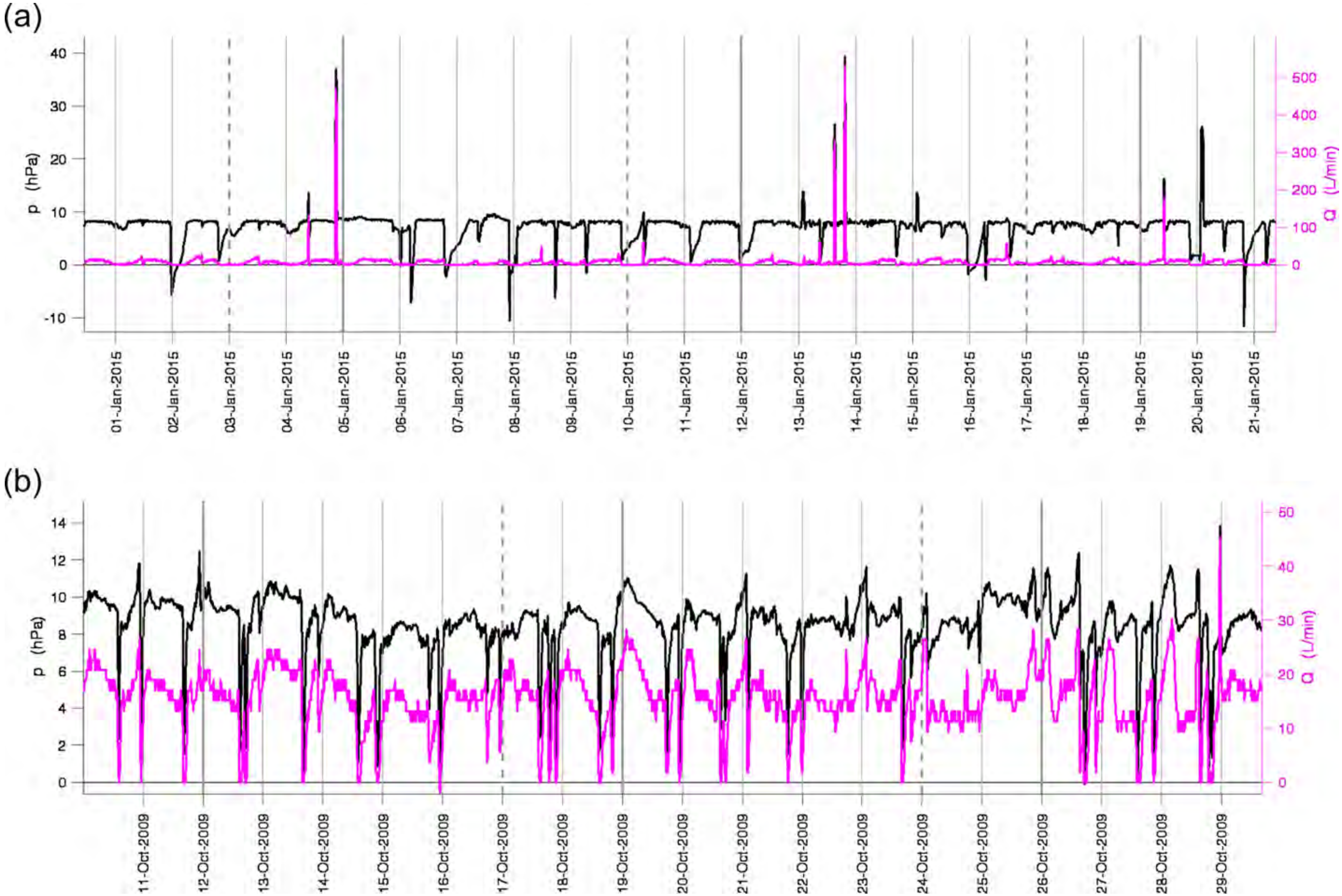

Fig. 2. Time series of ullage pressure p (left ordinate) and volumetric flow rate Q (right ordinate) for (a) GS-MW and (b) GS-NW. Horizontal tick marks indicate midnights. The vertical dashed and thick solid gray lines enclose weekends.

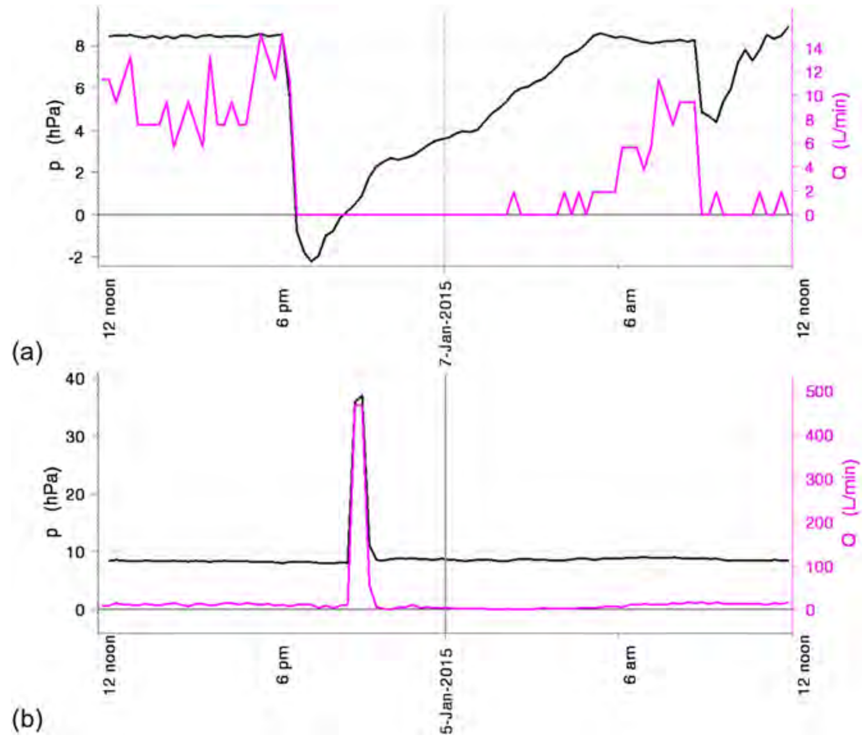

Fig. 3. Amplifications of time series data (15-minute averages) for GS-MW. (a) Tank pressure *p* became negative after fuel delivery. As a result, vent emission ceased for several hours. (b) A major vapor release (burst) likely occurred when the cracking pressure of the P/V valve was significantly exceeded at around 9 pm during a non-compliant bulk fuel delivery.

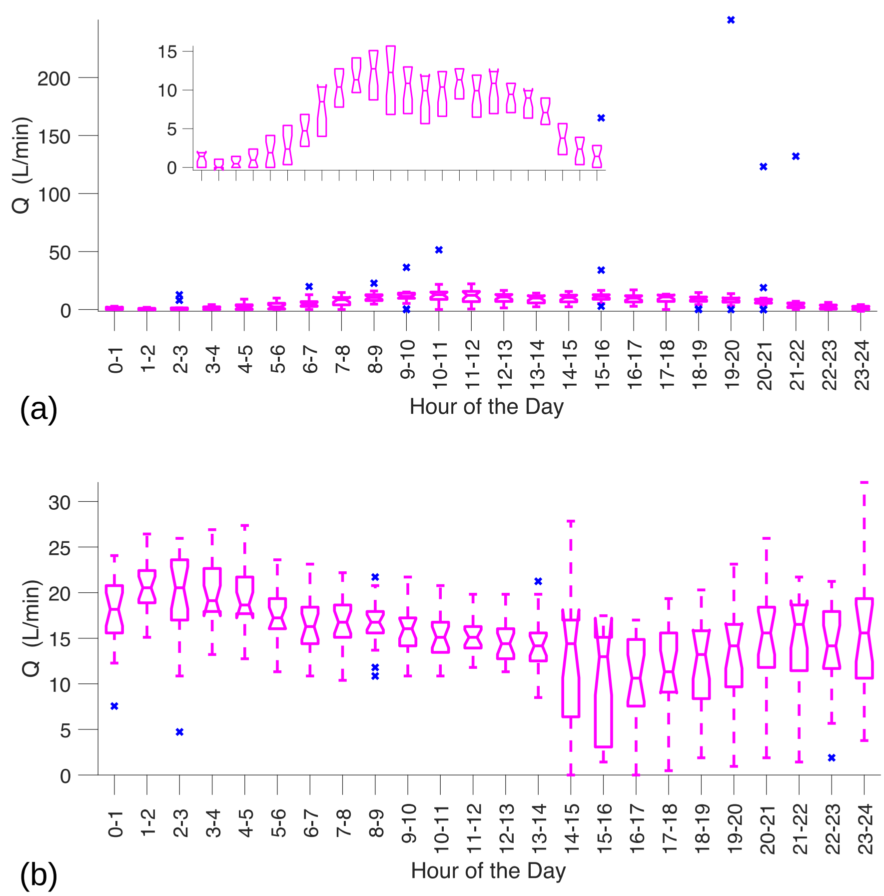

Fig. 4. Distribution of vent emissions Q observed for each hour of the day at (a) GS-MW [insert shows the IQRs of *Q*] and (b) GS-NW gas stations. In (a), outliers make it difficult to recognize variations in median hourly emissions. We therefore plotted in the inset only the IQRs. Boxes indicate median and IQR, whiskers values within 1.5 the IQR, and asterisks outliers.

Table 2
Summary of gas station characteristics and vent emissions.

	GS-MW	GS-NW	Units
Sales volume $\dot{V}_{sales}$	450,000	700,000	gal/month
Volumetric flow rates (of gasoline vapor/air mixture)			
Mean $\overline{Q}$	7.9	15.4	L/min
Median (IQR) of 60-min average	6.1 (1.9, 10.9)	16.0 (12.7, 18.4)	L/min
Maximum of 60-min average	250	32.1	L/min
Vent emission factor EF_{vent}	1.4	1.7	lb/kgal
Mass flow rates of gasoline (w/o air)			
Mean $\overline{\dot{m}}_{gas}$	0.39	0.76	kg/h
Maximum of 60-min average	12.3	1.6	kg/h
Correlation coefficient			
Between Q and p	0.58	0.85	–

shown in Fig. SI-2a. At a distance of 40 m, the REL was exceeded three times at one grid point (260° angle), and at 35 m four times at two grid points (250° and 260° angles) (Fig. SI-2b). At a distance of 20 m, the REL was exceeded at 30 (out of 36) grid points, and on nine different days.

Average benzene levels are shown in Fig. 6 for both gas stations. The MRL is exceeded at the elevation of the vent pipe opening, $z = 4$ m, up to 7 m away from for GS-MW and up to 8 m from GS-NW. Fig. 7 shows the average benzene concentration as a function of distance at an elevation of 2 m. Close to the center, benzene levels first increase and then decrease.

5. Discussion

5.1. Vent emission factors

We present unique data on vent emissions from USTs at two gas stations. Emissions can be compared to vent losses assumed by CAPCOA (CAPCOA, 1997). For a gas station with Stage I and II vapor recovery technology and a P/V valve on the vent pipe of the UST (Scenario 6B), the CAPCOA study assumed loading losses of 0.084 and breathing losses of 0.025 lb/kgal dispensed. The total loss of gasoline through the vent pipe is the sum of the two and amounts to a vent emission factor EF_{vent}= 0.109 lb/kgal. Based on actual measurements in two fully functioning US gas stations, we obtained EF_{vent} values of 1.4 lb/kgal for GS-MW and 1.7 lb/kgal for GS-NW, more than one order of magnitude higher than the CAPCOA estimate. While the difference between our measurements and the CAPCOA estimates may appear surprising, it is important to consider that the CAPCOA estimates are based on relatively few measurements and some unsupported assumptions (Aerovironment, 1994), particularly with regard to uncontrolled emissions due to equipment failures or defects (Appendix A-5 (CAPCOA, 1997)).

5.2. Pressure measurements

Tank ullage pressure p was moderately to strongly positively correlated with vent flow rate Q, likely because exceedance of the cracking pressure of the P/V valve causes a vent release. Thus pressure measurements can be used to infer vent releases. Real-time detection of equipment failures and leaks via so-called in-station diagnostics systems is based on our observed correlations between p and Q.

Table 3
Mean benzene emission rates $\dot{m}_{benz}$ for the two gas stations.

Emission source	Benzene emissions (mg/s)	
Gas station	GS-MW	GS-NW
Vent pipe	0.80	1.55
Spillage	0.39	0.65
Refueling	0.41	0.69
Hose permeation	0.06	0.10
Total	1.67	2.90

5.3. Diurnal fluctuations in vent emissions

Diurnal vent emissions were quite different at the two gas stations. At GS-MW, a 24-hour operation, vent emissions were high during the daytime, presumably due to PWD. Emissions ceased at night, likely because less gasoline was dispensed and fuel deliveries with relatively cool product were frequent. Evaporative losses could also have been lower at night because the cooler delivered fuel would cause slight contraction of the liquid phase with corresponding growth in the ullage volume while at the same time lowering the vapor pressure of gasoline in the UST.

At GS-NW, vent pipe releases occurred most of the time, during the daytime when fuel was dispensed (PWD) and at night when the gas station was closed. Vent releases were higher when the gas station was closed, suggesting that during the day-time Stage II vapor recovery resulted in the injection of vapors into the storage tank that were not completely equilibrated with the liquid gasoline. During night-time, the gradual equilibration of unsaturated air in the ullage of the UST with gasoline vapors could then have caused exceedance of the cracking pressure of the P/V valve and consequently vapor release. It seems counterintuitive that less nighttime emissions occurred at the gas station where fuel was dispensed. However, while fuel is being dispensed, the outgoing liquid creates additional ullage volume, and depending on excess air ingestion rate, a negative pressure could result that lowers vent pipe emissions.

Dispensing fuel to customer vehicles and the associated Stage II vapor recovery system interact with vent emissions and can even cause vent emission during PWD, because the vacuum-assist method can negatively interfere with Onboard Refueling Vapor Recovery (ORVR) installed in customer vehicles (EPA, 2004). However, Stage II vapor recovery is not obsolete. It can be used in conjunction with ORVR to minimize exposure of gas station customers and workers to benzene due to working losses (Cruz-Nunez et al., 2003), particularly when customer vehicles are not equipped with ORVR (e.g., older vehicles, boats, motorcycles) or small volume gasoline containers are refueled. Enhanced Stage II vapor recovery technology can significantly reduce vapor emissions both at the nozzle and from UST vent pipes (CARB, 2013).

5.4. Fuel deliveries and accidental vent releases

Based on observations and interpretation of time series of the tank pressure data, it is likely that the peak vent emissions (e.g., Fig. 3b) were partly due to non-compliant bulk fuel drops where the Stage I vapor recovery system either was not correctly hooked up by the delivery driver or to hardware problems with piping and/or valves. This

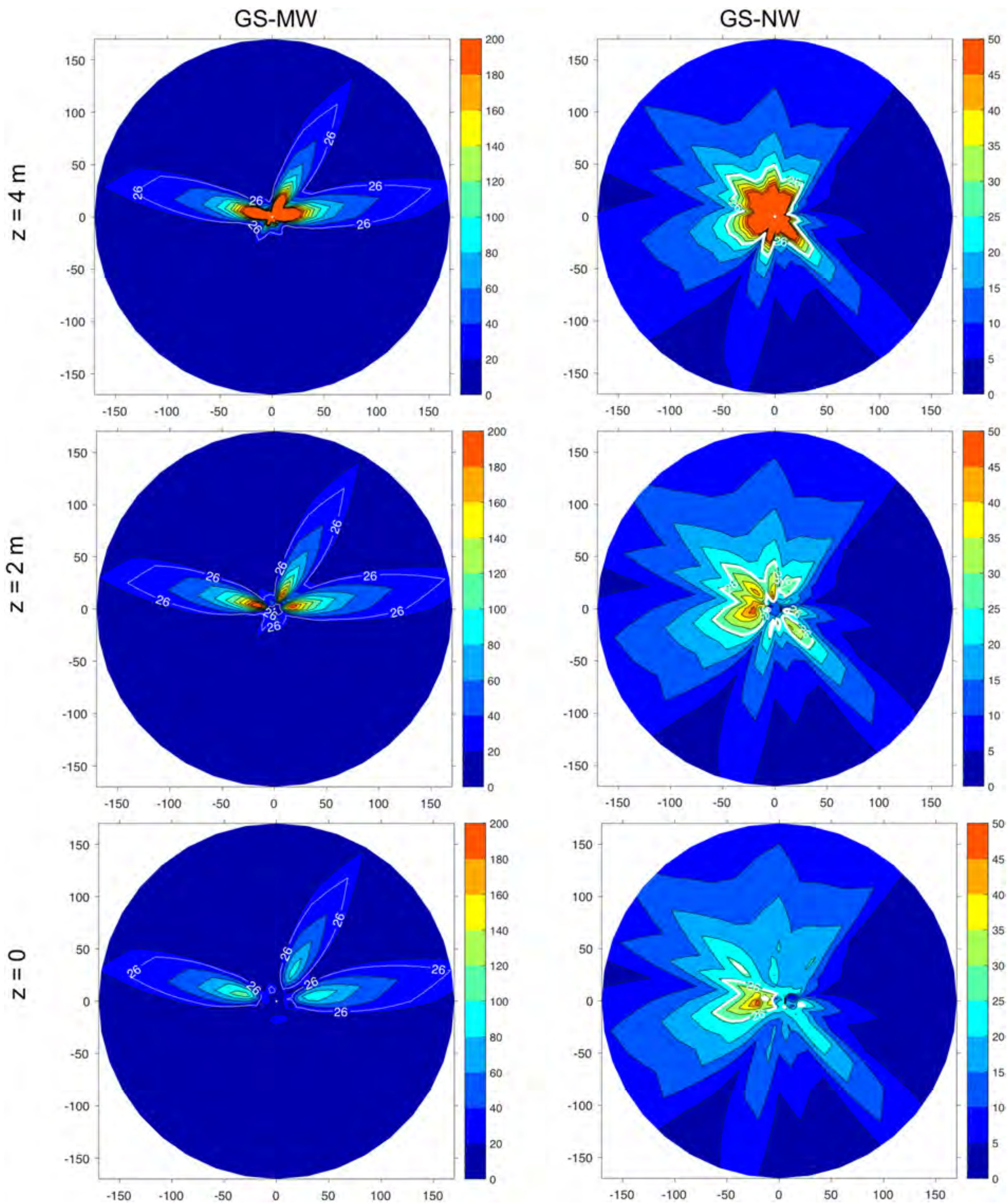

Fig. 5. Modeled maximum benzene concentrations for GS-MW and GS-NW at three different elevations *z*. The *x*- and *y*-axes indicate horizontal coordinates in meters. The color indicates benzene levels in units of μg/m^3. Left column: time series of benzene emission rates were used. Right column: average benzene emission rate was used in the modeling. The white isoline indicates OEHHA's acute REL of 26 μg/m^3 = 8 ppb.

conjecture is consistent with typical US storage tank volumes (~10,000 to 30,000 gal). Assuming that Phase I vapor recovery did not work at all and that 10,000 gal (~38,000 L) of fuel were delivered, the working loss (volume of gasoline vapor/air mixture released to the atmosphere through the vent pipe) is 38,000 L. It is also reasonable to assume that delivery lasted less than 1 h. According to Table 2, the maximum hourly flow rate through the vent pipe was 250 L/min at GS-MW, which would result in a maximum cumulative vapor release of 15,000 L within this hour. The measured maximum cumulative release underestimates the assumed working loss of 38,000 L. This could be due to a fuel delivery, which involved dropping fuel from multiple compartments of a tanker truck, with the vapor return hose not being correctly hooked up for only some of the emptied compartments.

At GS-MW, UST pressure decreased after fuel delivery (causing vent emissions to cease for several hours) during the climatic conditions prevalent during the observation period, behavior not observed at GS-NW. In practice, it is possible to observe both positive and negative pressure excursions, even during the same fuel delivery (when multiple fuel

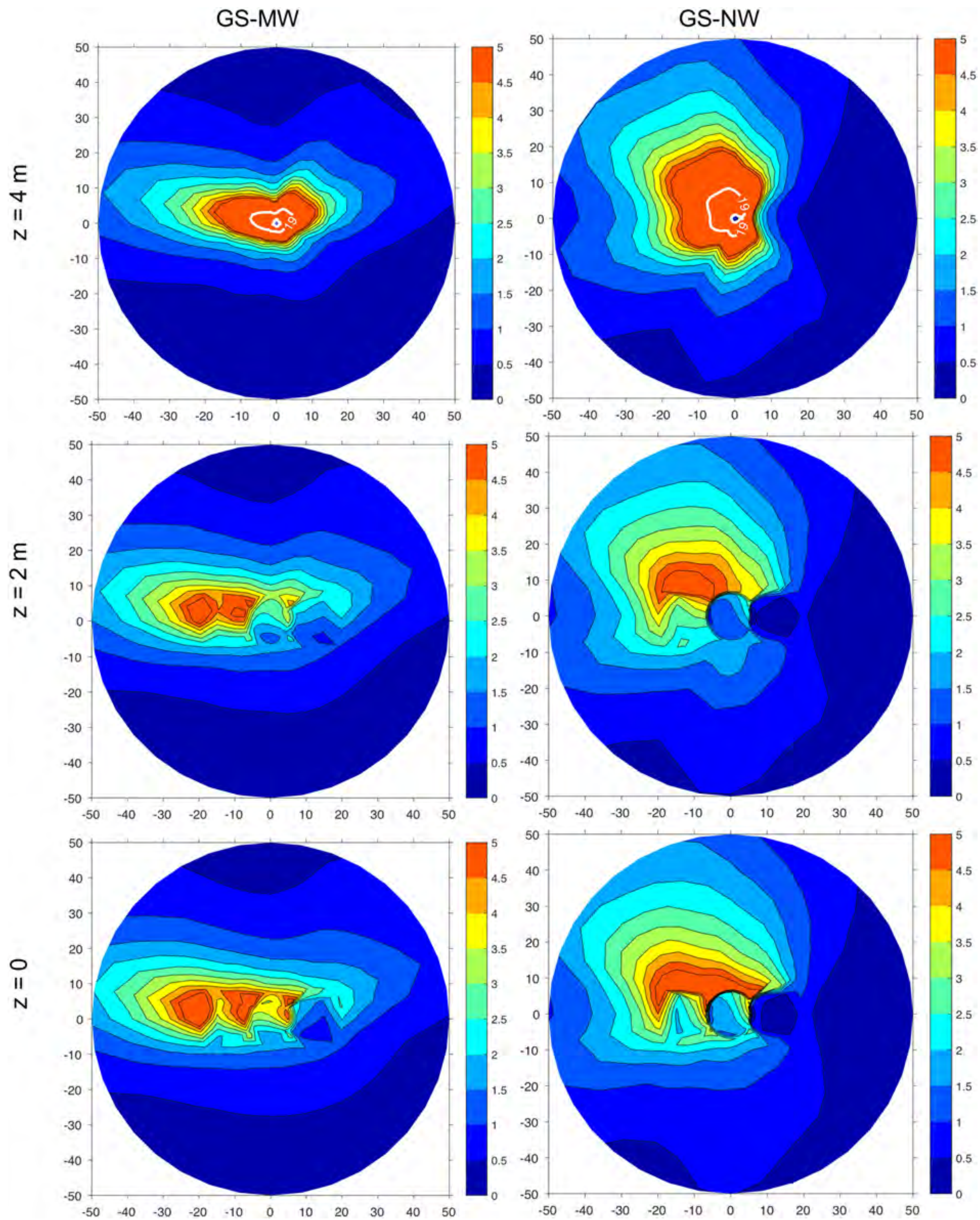

Fig. 6. Modeled average benzene concentrations for GS-MW and GS-NW at three different elevations *z*. The *x*- and *y*-axes indicate horizontal coordinates in meters. The color indicates benzene levels in μg/m^3 and the white isoline the MRL of 19 μg/m^3 = 6 ppb.

compartments of tanker trucks are unloaded), when Stage I vapor recovery is in place (personal observation by TT).

5.5. Exceedance of 1-hour exposure limits

AERMOD air pollution modeling suggests that at GS-MW the 1-hour acute REL was exceeded at one grid point 160 m (525 ft) from the center of the gas station once in 20 days (Fig. 5). This distance is larger than the 300-ft (91 m) setback distance recommended by CARB for a large gasoline dispensing facility (CalEPA/CARB, 2005). Assuming the gas station's fence line is <225 ft. (69 m) from its center (where the vent pipe was assumed to be located), our study shows that sensitive land uses at a distance further than 300 ft from the fence line of the gas station would represent a health concern despite compliance with the CARB guidelines because of non-compliance with the acute REL.

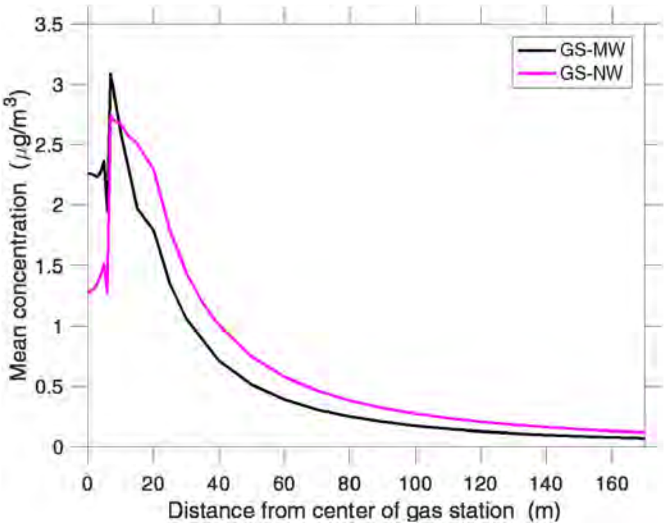

Fig. 7. Mean benzene concentrations as a function of distance from the center of the gas stations.

At any location further than 50 m from the gas station's center, the REL was exceeded at most once during the 20-day measurement campaign (Fig. SI-1a). However, exceedance occurred at several locations, and on two different days (Fig. SI-1b). E.g., at a distance of 120 m from the center, the REL was exceeded at three grid points, and the number of grid points increased with closer proximity to the gas station. This suggests that it was not just a single worst-case scenario or a single accidental vapor release that led to REL exceedance; rather exceedance may occur more frequently than is anticipated. Prevalent wind directions during the measurement campaign explained the directional patterns of exceedances (see the wind rose in Fig. SI-3a).

At GS-NW, despite its higher sales volume, the REL was exceeded only closer than 50 m from the gas station's center. However, exceedance occurred much more frequently (Fig. SI-2), likely because of the higher sales volume of GS-NW. Again, the wind rose for GS-NW (Fig. SI-3b) explains spatial patterns of REL exceedance.

None of AIHA's three ERPG levels were exceeded, meaning that individuals, except perhaps sensitive members of the public, would not have experienced more than mild, transient adverse health effects.

5.6. Average benzene levels

The initial increase in average benzene levels when moving away from the gas stations' centers (Fig. 7) is likely due to the vent emissions (at 4 m) which represent the largest benzene source, and which require a certain transport distance until they reach the 2-m level through dispersion. Further away from the gas station, benzene levels are higher for GS-NW than for GS-MW likely because of the higher sales volume of GS-NW. However, close to the center, benzene levels are higher at GS-MW. This can be attributed to the higher wind speeds at GS-NW (Table SI-1), which result in greater initial dilution of emitted pollutants in the incoming airstream and also in greater subsequent pollutant dispersion.

Modeled average benzene concentrations are generally lower (~10 μg/m^3 or less) than those measured in the surroundings of gas stations, likely because our simulations do not account for traffic-related air pollution (TRAP). For instance, a study published by the Canadian petroleum industry found average benzene concentrations of 146 and 461 ppb (466 and 1473 μg/m^3) at the gas station property boundary in summer and winter, respectively (Akland, 1993), values orders of magnitudes higher than ours. A South Korean study examined outdoor and indoor benzene concentrations at numerous residences within 30 m and between 60 and 100 m of gas stations and found median outdoor benzene concentrations of 9.9 and 6.0 μg/m^3, respectively (Jo & Moon, 1999), while we simulated benzene levels on the order of 1 μg/m^3 (Fig. 7). In a study on atmospheric BTEX levels in an urban area in Iran, the three highest BTEX levels were measured near gas stations (~150 m away); the measured benzene levels (64 ± 36, 31 ± 28, 52 ± 26 μg/m^3) were again much higher than ours simulated at that distance, likely due to TRAP. Our modeled average benzene levels at a distance of about 50 m are on the same order as background benzene levels of 1.0 μg/m^3 that were measured in 2010 in the National Air Toxics Trend Sites (NATTS) network of 27 stations located in most major urban areas in the US (Strum & Scheffe, 2016). However, our modeled levels at a distance of 170 m were 0.07 at GS-MW and 0.12 at GS-NW, a non-negligible addition to urban background levels.

At both gas stations, the MRL was exceeded at the level of the vent pipe opening in the vicinity of the gas stations, up to 7 m away from the vent pipe at GS-MW and 8 m at GS-NW. Therefore there might be an appreciable risk of adverse noncancer health effects for individuals living at the 2nd-floor level relatively close to high-volume gas stations such as GS-MW and GS-NW.

5.7. Limitations

A limitation of our study is that data were collected only in fall and winter. Results cannot be easily extrapolated to other seasons, because vent pipe emissions are seasonally dependent, e.g., due to seasonally dependent gasoline formulations and meteorological conditions. However, modeled exceedance of the OEHHA acute REL in the winter season is already of concern, because that REL was developed for once per month or less exposures.

Another limitation is that we did not directly measure benzene levels in the vent pipe, and instead made assumptions about vapor composition that were also made in the CAPCOA study (CAPCOA, 1997) of gas station emissions. In practice it may be difficult to obtain permission from gas station owners to measure benzene levels directly.

In part because we did not want to reveal the locations of the gas stations, we did not use site-specific topography information in the air dispersion modeling and instead assumed flat terrain. While this simplification results in less accurate air pollution predictions for the two sites, using a "generic" gas station is perhaps more representative of other gas station sites, and is consistent with an approach used in a previous study (CAPCOA, 1997).

Finally, our study did not predict benzene levels in indoor environments. Even though indoor air pollution levels may substantially differ from outdoor levels due to indoor sources (e.g., smoking, photocopying) (El-Hashemy & Ali, 2018), our study can still inform exposure levels in indoor environments as outdoor sources may be the main contributors to indoor air pollution, e.g., in buildings situated in urban areas and close to industrial zones or streets with heavy traffic (Jones, 1999). This is relevant to workers and customers in C-stores or other fast-food/gasoline station combination facilities.

6. Conclusions

Our study is to the best of our knowledge the first one to (1) report hourly vent emission data for gasoline storage tanks in the peer-reviewed literature and (2) use these data in hourly simulations of atmospheric benzene vapor transport. This allowed us to examine potential exceedance of short-term exposure limits for benzene. Prior studies including CAPCOA's (CAPCOA, 1997) could not do so as average emission rates were used (only meteorological data was used at an hourly resolution).

Our findings support the need to revisit setback distances for gas stations, which are based on >2-decade old estimates of vent emissions (Aerovironment, 1994). Also, CARB setback distances are based on a binary decision, related to whether the gasoline sales volume $\dot{V}_{sales}$ is >3.6 million gal per year. Our data support, however, that setback distances should be a continuous function of sales volume $\dot{V}_{sales}$ and also include the type of controls installed at the facility. Setback distances should also address health outcomes other than cancer. OEHHA's acute REL for benzene could be used to inform setback distances as it accounts for non-cancer adverse health effects of benzene and its metabolites (Budroe, 2014). ATSDR's MRL could also be considered since it is a health-based limit.

We note that CARB recommended their setback distances in 2005, presumably assuming pollution prevention technology yielding a 90% reduction in benzene emissions (CalEPA/CARB, 2005). Since then, CARB further promoted use of second-generation vapor recovery technology (Enhanced Vapor Recovery, EVR) to reduce emissions further. EVR includes technology that is supposed to prevent fuel vapors in overpressurized tanks from being expelled into the atmosphere (CARB, 2017). To that end, "bladder tanks" have been proposed, into which the gasoline vapor/air mixture is directed as the pressure in the combined ullage space of the storage tank increases, and from which the mixture is redirected into the fuel storage tanks if the ullage pressure becomes negative (when fuel is dispensed). The challenge with such a system is to ensure that the bladder tank capacity is not exceeded by the fuel evaporation rate. Alternatively, fuel vapor release can be reduced by processing the fuel/air mixture through either a semi-permeable membrane which selectively exhausts clean air and returns enriched fuel vapor (Semenova, 2004) or an activated carbon filter which adsorbs hydrocarbons (and water vapor) and exhausts air into the atmosphere, or by combusting the fuel/air mixture which would otherwise be released through the P/V valve. Therefore, current CARB setback distances might be adequate for gas stations in California but less so for the other 49 US states, and other countries—depending on pollution prevention technology requirements.

The larger areal extent of modeled REL exceedance at GS-MW is due to "accidental" releases of gasoline vapors. Even though regulations appear generally not to be driven by accidental releases, at GS-NW such releases likely led on two different days to REL exceedances at distances beyond CARB's recommended setback distances. Policies should address accidental fuel vapor releases that depending on pollution prevention technology (here Stage I vapor recovery) and its proper functioning can occur on a frequent basis (twice at GS-MW within about three weeks).

In future work, potential exceedance of other shorter-term exposure limits should be examined, e.g., the 15-minute short-term exposure limits (STELs) and the 8-hour time-weighted averages (TWAs) used for occupational exposures.

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Competing financial interest declaration

TT directs a company (ARID), which develops technologies for reducing fuel emissions from gasoline-handling operations. AMR, BAM and MH have no conflicts of interests to declare.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2018.09.303.

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2020 Study
Gasoline Vapor Emissions During Vehicle Refueling Events in a Vehicle Fleet Saturated With Onboard Refueling Vapor Recovery Systems - Need for an Exposure Assessment

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Gasoline Vapor Emissions During Vehicle Refueling Events in a Vehicle Fleet Saturated With Onboard Refueling Vapor Recovery Systems: Need for an Exposure Assessment

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Shearston JA and Hilpert M (2020) Gasoline Vapor Emissions During Vehicle Refueling Events in a Vehicle Fleet Saturated With Onboard Refueling Vapor Recovery Systems: Need for an Exposure Assessment. Front. Public Health 8:18. doi: 10.3389/fpubh.2020.00018

Background: Gasoline contains large proportions of harmful chemicals, which can be released during vehicle refueling. Onboard Refueling Vapor Recovery (ORVR) can reduce these emissions, but there is limited research on the system's efficacy over time in an actual vehicle fleet. The aims of this study are: (1) determine the feasibility of using an infrared camera to view vapor emissions from refueling; (2) examine the magnitude of refueling-related emissions in an ORVR-saturated fleet, to determine need for an exposure-assessment.

Methods: Using an infrared camera optimized for optical gas imaging of volatile organic chemicals, refueling was recorded for 16 vehicles at six gas stations. Pumps were inspected for damage, refueling shut-off valve functioning, and presence of Stage II Vapor Recovery. Vehicle make/model and age were recorded or estimated.

Results: Vapor emissions were observed for 14 of 16 vehicles at each station, with severity varying substantially by vehicle make/model and age. Use of an infrared camera allowed for identification of vapor sources and timing of release, and for visualizing vapor trajectories.

Discussion: Notably emissions occurred not only at the beginning and end of refueling but also throughout, in contrast to a prior study which did not detect increases in atmospheric hydrocarbon levels mid-refueling. Future studies are vitally needed to determine the risk to individuals during typical refueling in an ORVR saturated vehicle fleet. We recommend comprehensive exposure-assessment including real-time monitoring of emitted volatile organic compounds paired with infrared gas-imaging and measurement of internal dose and health effects of gas station customers.

Keywords: gasoline, environmental exposure, vehicle refueling, volatile organic compounds, gas station

INTRODUCTION

Gasoline is a complex mixture of many chemicals, several of which are known to adversely affect human health. Of particular concern are volatile aromatic hydrocarbons, including benzene, toluene, ethylbenzene, and xylene (BTEX group), which may be released during vehicle refueling (1, 2). For example, benzene is a known human carcinogen and is associated with multiple health problems, including respiratory, nervous system, and immunological conditions (3). In addition, studies evaluating non-cancer outcomes have found decreased red blood cell counts, hemoglobin, and hematocrit levels in gas station attendants (4). While some studies have evaluated exposures to gasoline from vehicle refueling specifically (5–7), to our knowledge, few have been completed in the past decade. It is essential that such studies are repeated frequently and in varied geographic locations, as fuel composition, weather, climate, and pollution control strategies all impact individual exposures and can change over time.

In the United States (US), changes in regulations outlining gasoline vapor recovery during vehicle refueling have made this an especially pressing question. During refueling, gasoline vapor in a vehicle's tank is pushed into the atmosphere by the rising liquid gasoline level in the tank—unless a vapor recovery system is in place. From 1998 to 2006, the US Environmental Protection Agency (EPA) rolled out a requirement that nearly all newly manufactured vehicles be equipped with onboard refueling vapor recovery (ORVR) systems (8), which function by directing vaporized gasoline into a canister on the vehicle, thereby substantially reducing escape of vapors into the atmosphere. Briefly, this requirement was rolled out in stages, first for light duty vehicles (1998: 40% of new vehicles, 1999: 80%, 2000: 100%), then for light duty trucks and vans (2001: 40%, 2002: 80%, 2003: 100%), and finally for heavier light duty trucks (2004: 40%, 2005: 80%, 2006: 100%) and trucks with a >10,000 pounds gross vehicle weight rating (100% by 2006). By 2006, nearly all new gas-powered vehicles with <14,000 pound gross vehicle weight rating were required to have ORVR systems (8). In contrast, Stage II vapor recovery systems, which are used on gasoline pumps themselves, direct vaporized gasoline into gas station underground storage tanks through systems on the pumps. In 2012, the EPA determined that the US vehicle fleet was sufficiently saturated with ORVR that states could allow the removal of Stage II systems (8), thus making vapor recovery during refueling primarily dependent on ORVR systems.

Despite this change in regulations, limited information on the efficiency of ORVR systems is available, although the US EPA suggests they are 98% efficient and require minimal maintenance (8). A German study found no measurable increases in atmospheric hydrocarbon concentrations in a Sealed Housing for Emissions Determination (SHED) in which an ORVR-equipped vehicle was placed during refueling, although increases were detected at the beginning and end of refueling (9). Even though a study of presumably non-ORVR equipped vehicles in Mexico found older vehicles to have more evaporative emissions than newer ones (10), to the best of our knowledge, no assessment of the continuous functioning of ORVR systems to reduce emissions during vehicle refueling over the course of a vehicle's lifetime, within the conditions of an actual vehicle fleet, has been completed. It is possible that as vehicles age, hoses, seals, and other parts of the gas tank and ORVR system degrade, resulting in increased vapor emissions during refueling. Additionally, while some studies (6, 7) evaluated exposure to gasoline vapors during vehicle refueling in the US, finding evidence of benzene in blood and exhaled breath samples, those studies were completed before saturation of the US vehicle fleet with ORVR systems, and are thus likely over-estimates of exposures that may occur with ORVR systems. It is not currently known whether the amount of vapors today's population is exposed to would have similar, if any, effects.

Past studies assessing exposure from vehicle refueling used aluminum tubes as passive samplers (7) and sorbent tubes attached to pumps (6) to quantify exposure to gasoline vapors, positioned in the breathing zone of participants. However, such methods may not be able to detect the lower levels of exposure anticipated from a vehicle fleet with a 98% efficient ORVR system. Additionally, while these methods quantify environmental exposure to vapors during refueling, they are not easily used for source identification or to capture the dispersion and movement of vapors at the station. It is also not possible to use these devices to determine when during a refueling event vapors are more likely to be released (i.e., at the end vs. throughout), information which can help determine the cause of vapor release. Use of other technologies, such as an infrared camera optimized for visualizing compounds present in petroleum products, is needed to determine the sources of vapors during refueling (i.e., from exhaust, the vehicle tank, or the pump nozzle) and how they move through space. Such cameras are also fine-tuned to detect very small amounts of vapors, and thus may be invaluable in determining if exposure to gasoline vapors is occurring from ORVR equipped vehicles, warranting a more involved exposure-assessment.

Research on the functioning of ORVR in the actual US vehicle fleet over time, and thus an understanding of the quantity of vapors individuals may still be exposed to, is limited. Additionally, the tools traditionally used to assess exposure to vapors during vehicle refueling do not give a complete picture, as they lack the ability to determine vapor sources and movement. With this pilot study, we aim to determine the plausibility and usefulness of conducting a full exposure-assessment for exposures to gasoline vapors during vehicle refueling, in a vehicle fleet dependent on ORVR for vapor recovery. The objectives of this pilot study are to (1) determine the feasibility of qualitatively capturing fuel vapor emissions from vehicle refueling events in New York City (NYC) using a FLIR infrared camera designed specifically to detect volatile organic compounds present in petroleum products, and to (2) examine the magnitude of fuel vapor emissions over a range of different vehicle/ORVR system ages as a precursor to assessing the continuous functioning of ORVR systems over the lifetime of a vehicle in the actual US vehicle fleet.

MATERIALS AND METHODS

Study Overview

A convenience sample of gas stations in Northern Manhattan, NYC, was selected for vapor release monitoring. At each gas station, a study member approached individuals just before they began refueling their vehicles and asked for verbal permission to record their vehicle tanks as the vehicle was refueled. This study is not human subjects research, as no information about individuals was obtained, and is thus not subject to IRB oversight.

A total of six gas stations were visited over the course of a single winter day. Three vehicle refueling events were recorded at each station, with the exception of one station where an attendant was present. For this station, only one vehicle refueling event was recorded. In total, $n = 16$ refueling events were recorded.

Data Collection

An infrared camera optimized for optical gas imaging of volatile organic chemicals (FLIR model GF320; described below) and frequently used to detect leaks in petroleum refining operations, was used to record the fuel pump nozzle and external vehicle fuel tank filler pipe during each refueling session. In addition, researchers visually inspected gasoline pumps for hose damage, refueling shut-off valve functioning, and presence of Stage II Vapor Recovery systems. Researchers recorded the make and model of the vehicle when it was visible on the outside of the automobile, while year was estimated using photographs of the vehicle. Year was estimated by searching for images of the vehicle make and model, and comparing different years, especially the front and rear bumpers and headlight shape, to those shown in the photographs. When researchers could not definitively determine the year of the vehicle, the midpoint of the plausible year range was used. Vehicles were assigned a type based on the EPA Vehicle Classification system.

Overview of FLIR Infrared Camera

The FLIR model GF320 infrared camera can detect 20 gases, including: 1-pentene, benzene, butane, ethane, ethanol, ethylbenzene, ethylene, heptane, hexane, isoprene, m-xylene, methane, methanol, methyl ethyl ketone, MIBK, octane, pentane, propane, propylene, and toluene (FLIR Systems Inc., 2017). The camera is tuned to detect very small spectral ranges, so that it can selectively visualize specific compounds that absorb or emit electromagnetic energy at that spectral range. A narrow bandpass filter is used to ensure that only gases with a strong signal in the specified infrared range are detected, and other components of the camera are built to emit very little energy, to reduce the signal-to-noise ratio. The manufacturer does not provide estimates of limits of detection of their camera, but we found that the GF320 can detect quite small vapor leakage rates, e.g., gas emissions from an unignited pocket lighter in outdoor atmospheric environments imaged from a distance of at least 2 m.

Qualitative and Statistical Analysis

To determine how representative our convenience sample is of New York State and New York City vehicle fleet ORVR saturation, we used New York State's publicly available Vehicle, Snowmobile, and Boat Registrations database to calculate the proportion of registered vehicles in both the state and city that were gasoline powered and manufactured in 2006 or later (out of all gasoline powered vehicles), the year the EPA suggests that "essentially all" new gas-powered vehicles <14,000 pounds were manufactured with ORVR systems (8). We compared this to the proportion of ORVR equipped vehicles in our sample. In addition, we compared the median vehicle manufacturing age in our sample to that of registered vehicles in New York State and City.

Each infrared video was reviewed to identify the presence and magnitude of vaporized gasoline emitted during a refueling session. An overall qualitative description of each video was created, and patterns of vapor emission were identified and assigned to each session. Vapor origin (i.e., ambient vapors vs. vapors from the vehicle fuel tank) and the timing of vapor release was reviewed in all sessions. Representative video frames of "typical" emissions for each vehicle were extracted from the middle and end of each refueling session. The vapor plume was delineated using the brush feature in Microsoft Paint based on repeated observations of the videos, and not just a single frame, as it is difficult to identify the plume from a static image.

Exploratory statistical analysis was conducted in R version 3.5.1 (11). A logistic model was fit to obtain an association between estimated vehicle age and presence of vapor release during the middle of vehicle refueling, operationalized as a binary variable. Due to the small sample size no covariates were included in the model.

Figures were created with the tidyverse package in R (12), as well as with Inkscape (www.inkscape.org) and MATLAB (The MathWorks Inc., 2010).

RESULTS

A total of 16 refueling events at six gas stations were recorded. Our convenience sample was fairly representative of the estimated ORVR penetration proportion in New York State and City vehicles: according to EPA regulations 94% of our sample should have been equipped with ORVR, while for both New York State and City, we estimate that at least 81% of registered vehicles should have been equipped with ORVR. The median manufacturing year of our sample was 2013, the same as that for New York State and City.

Table 1 provides details about gas stations and vehicles. Of the six stations, only one had a Stage II vapor recovery system, and four had liquid gasoline leaking around the hose joints. Estimated vehicle age ranged from 1 to 32 years (manufacturing years 1987–2018), and several vehicle types (e.g., SUV, mid-size car) were represented in the sample. For 15 out of 16 vehicles, vehicle age and type combination indicated they were required to contain ORVR systems. The average refueling length was 86 s. Ambient temperature ranged from 33 to 41°F (0.5–5°C).

The infrared camera was able to detect gasoline vapors during vehicle refueling. In addition, evaluation of the video files allowed researchers to identify vapor sources, pinpoint the time of vapor release during each video, and to see how the vapors moved after being emitted.

TABLE 1 | Characteristics of gas stations and vehicle refueling events.

Gas station ID	Stage II vapor recovery system	Hose joints	Vehicle ID	EPA vehicle size classification	Estimated model year	ORVR mandate*	Length of refueling (s)
2	None	No leakage	29	Minicompact car	2014	Yes	66
			30	Midsize car	2005	Yes	88
			32	Standard sport utility vehicle	2013	Yes	88
3	None	Leakage	33	Midsize car	2006	Yes	76
			34	Mid-size car	2018	Yes	78
			35	Small sport utility vehicle	2013	Yes	84
4	None	Leakage	36	Mid-size car	2008	Yes	131
			37	Standard sport utility vehicle	2018	Yes	133
			38	Standard sport utility vehicle	2015	Yes	71
8	Vacuum assist	Leakage	41	Compact car	2005	Yes	72
			42	Midsize car	2016	Yes	122
			43	Midsize car	2008	Yes	66
9	None	Leakage	44	Standard sport utility vehicle	2004	Yes	56
			45	Large car	1987	No	110
			46	Midsize car	2015	Yes	106
7	None	No leakage	47	Minivan	2013	Yes	32

**Indicates whether 100% of new vehicles were required to have included ORVR systems for the specific manufacturing year and vehicle type (i.e., light duty vehicle, light duty truck, and van, heavier light duty trucks, etc.).*

Fuel vapor emissions were observed for 14 out of 16 vehicles and at every gas station. The single vehicle older than ORVR manufacturing mandates in the US clearly had much larger refueling vapor emissions than the newer vehicles. However, the majority of newer vehicles also had substantial fuel vapor emissions, particularly at the end of refueling. Qualitative descriptions of each refueling event are provided in **Table 2**. Six overall patterns of vapor emission were identified: no vapor release (one vehicle), ambient vapors only (one vehicle), release toward the end of refueling (two vehicles), release when nozzle was withdrawn (three vehicles), release toward the end of refueling and after nozzle was withdrawn (six vehicles), and near continuous vapor release (three vehicles). **Figure 1** shows the number of vehicles in each category, and the years of the vehicles' manufacture. The three vehicles with near continuous vapor release were estimated to be 5, 11, and 32 years old. Of note, all vehicles that emitted vapors at any point during the refueling session also did so at the end of the refueling session.

Representative video frames from the middle and end of each refueling session are available in the **Supplementary Material** (two frames per vehicle). In **Figure 2**, examples from each of the six vapor emission patterns are shown, with gasoline vapor plumes delineated in blue in each frame, and vehicle IDs in the top right corner. For example, for the "release when nozzle withdrawn" category, the representative screenshot during the middle of the refueling session does not show any vapors, however, at the end of the session, vapors can be seen spilling out around the pump nozzle and the vehicle fuel tank opening. The range of emission magnitude can be seen from the various sample frames. Full video recordings for each refueling event are available at the following link: https://github.com/jenni-shearston/Vehicle_Refueling_Videos.

Results from the exploratory logistic regression were not significant, as there were not enough observations to detect an association ($n = 16$; yes release [$n = 3$]/no release [$n = 13$]). The model suggested that a 1 year increase in estimated vehicle age was associated with a 1.15 increase in likelihood of emitting vapors during the middle of refueling (95% CI = 0.97, 1.51), but this result is likely driven by the results for the 32 years old vehicle, which was much older than the rest of the vehicle population.

DISCUSSION

This work highlights the value of using an infrared camera to compliment more traditional methods of exposure measurement for determining potential health risks from vehicle refueling, and visually highlights the sometimes large amounts of fuel vapor emissions that occur even within an ORVR saturated vehicle fleet.

A FLIR camera allowed us to identify the source of the vapors; for example, in one video (Vehicle ID 44) vapors can be seen, but they do not originate from the pump nozzle or the vehicle tank. Of note, we observed leaking gasoline around the hose joints at this station (Station 9). For all other videos, vapors are clearly seen coming out of the pump nozzle, vehicle tank, or both. This allows for the differentiation of sources of vapor exposure, crucial information needed to intervene on exposures at gas stations generally, or to determine how effective ORVR is at minimizing vapor outflow. In addition, use of the infrared camera allowed us to confirm that vapors were emitted in a location where an individual filling up their gas tank might breathe them in (the "breathing zone"), and to visualize the dispersion and movement of the vapors. The infrared camera also made it possible to pinpoint when during a refueling session

TABLE 2 | Qualitative description and overall patterns of vehicle refueling events.

Vehicle ID	Qualitative description	Overall pattern
29	Some gasoline vapor can be seen escaping into the atmosphere from the beginning of the refueling event, continuing throughout the duration of refueling. At around 0:00:41, a larger amount of vapor is seen escaping from the vehicle tank, generally increasing in amount until the end of the refueling session	Near continuous vapor release
30	No vapors are seen escaping into the atmosphere until more than a minute of refueling has passed (0:01:13), after which a large amount of vapor escapes as the vehicle tank presumably reaches full	Release toward end of refueling
32	Minimal vapor was released into the atmosphere throughout the duration of the refueling event. At the very end of refueling, as the pump is removed from the tank, a small amount of vapor can be seen escaping	Release toward end of refueling and after nozzle withdrawn
33	No vapors are seen escaping from the vehicle tank until the end of refueling, around 0:01:13, after which a large amount of vapor escapes, presumably as the tank reaches full. After the pump is withdrawn from the tank, fuel vapor continues to escape into the atmosphere in substantial quantities	Release toward end of refueling and after nozzle withdrawn
34	No vapor is seen escaping until the end of the refueling session, around 0:01:11, after which a substantial amount of fuel escapes into the atmosphere, continuing to escape even after the pump is withdrawn from the vehicle	Release toward end of refueling and after nozzle withdrawn
35	No vapor is seen escaping from the vehicle tank until the end of refueling. Vapors escape when the pump handle is partially withdrawn (0:01:12) and the tank is presumably topped off, and continue to escape even after the pump is fully withdrawn	Release toward end of refueling and after nozzle withdrawn
36	Although the pump is inserted into the vehicle from the beginning of the video, it appears that fuel is not dispensed until around 0:00:43 when the individual's hand squeezes the pump handle. As dispensing begins, large amounts of vapors can be seen escaping from the tank. Of note, the individual refueling does not fully insert the pump into the tank. Vapors escape nearly continuously throughout refueling, sometimes in large amounts. Toward the end of the session another large amount of vapor escapes, as the pump is pulled further out of the vehicle (0:01:55). Substantial amounts of vapor continue to escape until the end of refueling, including after the pump is fully withdrawn (0:02:49)	Near continuous vapor release
37	No vapor release observed	No vapor release
38	No vapor is observed until around 0:00:51, after which vapor is released nearly continuously. Vapor is observed escaping from the tank after the pump is withdrawn	Release toward end of refueling and after nozzle withdrawn
41	Some vapor is released at the beginning of the refueling session (0:00:14), but no more is observed until toward the end of refueling around (0:01:08). After this time, vapor is observed in substantial quantities until the pump is withdrawn (0:01:21), after which only minimal vapors are observed escaping	Release toward end of refueling
42	No vapors are observed until the very end of refueling, when the pump is withdrawn (0:01:59). Vapor continues to be released from the tank until it is capped	Release when nozzle withdrawn
43	No vapor release observed during refueling; a small amount of vapor may be released after pump is withdrawn (0:01:08)	Release when nozzle withdrawn
44	Poor video focus makes vapor observation difficult; however, ambient vapors appear to be present (upper right, 0:00:35, 0:00:40, 0:00:54)	Ambient vapors only
45	Substantial vapor release observed as cap is removed from tank, and continuously throughout refueling	Near continuous vapor release
46	No vapor release observed during refueling; a slight amount of release from pump observed as it was removed from tank (0:01:57)	Release when nozzle withdrawn
47	Slight amount of vapor release observed at start of refueling (0:00:03), and then again at end of refueling (0:00:24). Vapor continues to be released after pump removed	Release toward end of refueling and after nozzle withdrawn

vapors were released. Sorbent tubes attached to pumps, passive samplers, and real-time monitors are not able to do this because the amount of vapor measured is averaged over a time period, so it is challenging to determine when the vapor is released, or if it is released continuously.

Information about the timing of vapor releases is particularly useful because it can help researchers determine why vapors are being released. For example, ORVR systems with "liquid seals" are known to release some vapors at the end of refueling (13), because as the flow of gasoline into the vehicle tank decreases, the air gradient into the tank created by the moving gasoline decreases, allowing vapors to flow both into the tank and out of it (and thus into the atmosphere) (9). Release at the end of vehicle refueling was indeed one of our most common observations. However, vapor releases occurring in the middle of the refueling session, or throughout the session, both of which we observed in multiple refueling events, may suggest a breakdown in functioning of the ORVR system. These findings appear to be inconsistent with the ones by Tumbrink who did not observe measurable emissions during refueling (9). Ren and Hao in China did find measurable emissions throughout refueling, but at low levels, with vapor concentration increasing over time and ranging from 0 to 4.5 mg/m^3 (13). Emissions could be the result of a leak in part of the vehicle's fuel system, aging of the activation sites or oversaturation of the charcoal filter used in the ORVR, or a malfunctioning mechanical seal. It is also possible that that the pump nozzle itself is damaged, resulting in vapor release. In addition, Ren and Hao found that ambient temperature, fuel temperature, filling flow, and filling pipe diameter all have an impact on the time to liquid seal formation and on vapor emissions (13). Emissions were increased when either ambient or fuel temperature was higher (13). As our study was conducted at cold ambient temperatures (0.5–5°C), we expect that emissions during Spring, Summer, and Fall would be greater than what we observed.

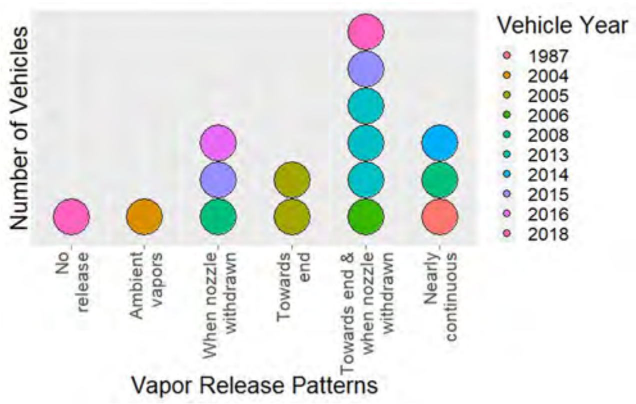

FIGURE 1 | Dotplot depicting the number of vehicles in each vapor release category (each dot represents one vehicle), with year delineated by color.

Our study found an average refueling time of 86 s (1.43 min), similar to the 1.13 min found by Vainiotalo et al. (5) in Finland and less than that found by Egeghy et al. (7) in North Carolina (median of 3 min). These studies, and others, included various biomarkers and measures of exposure: internal dose (blood) (6), exhaled breath (7), and breathing zone air (5–7), all of which suggested individuals were exposed to benzene, a known human carcinogen, during refueling. As all studies were conducted before widespread adoption of ORVR and only at gas stations without Stage II vapor recovery, their results are likely not representative of the typical exposure today. Somewhat concerningly, however, our study suggests that despite extensive use of ORVR, individual exposures at similar magnitudes to those experienced before ORVR requirements were implemented may still occur—two of the three refueling

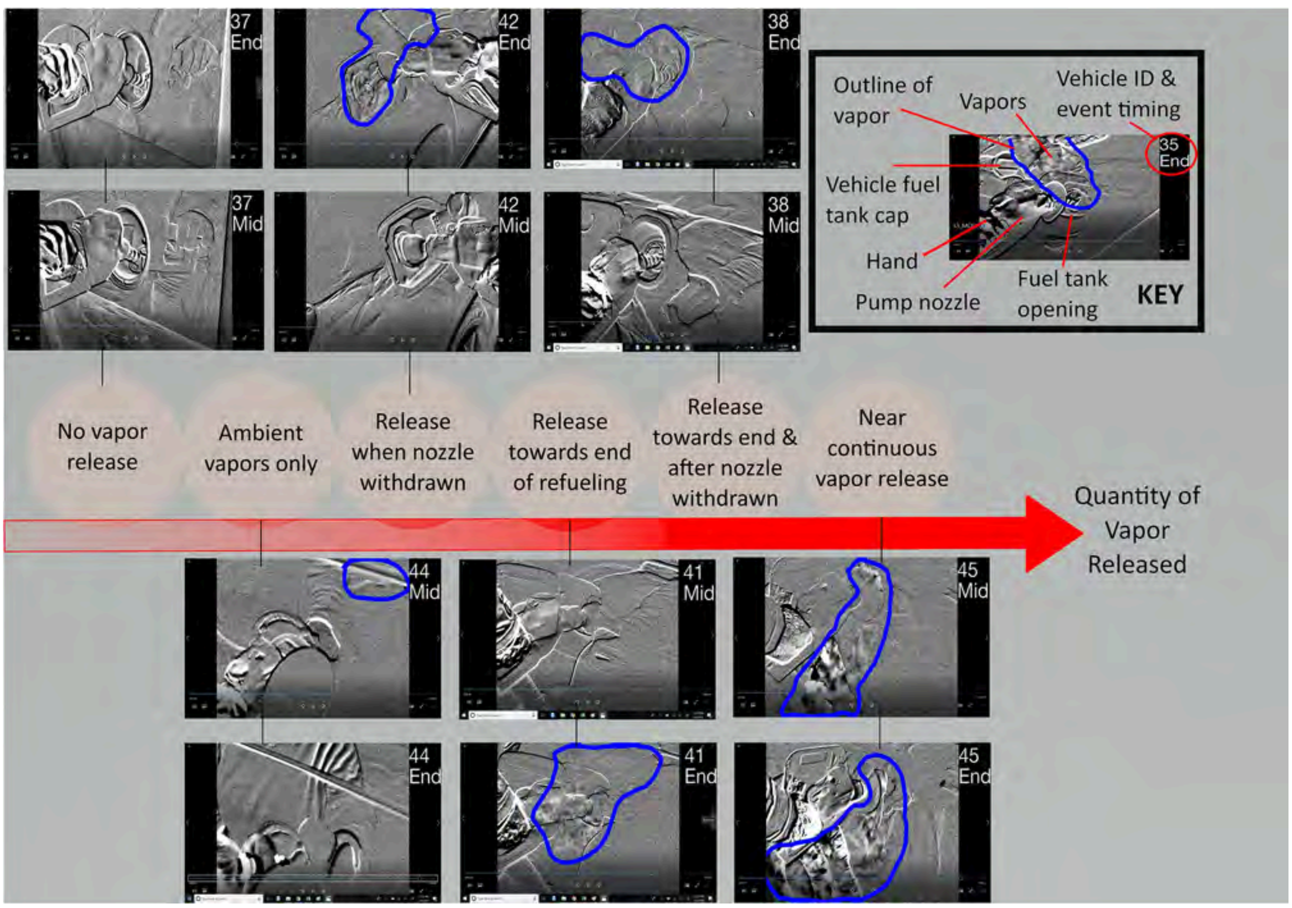

FIGURE 2 | Two sample frames for each of the 6 identified patterns of vapor release during refueling: one during the middle of the refueling session, and one at the end. Vehicle ID and an indicator for middle ("Mid") or end ("End") of the video are included in the upper right corner of each photo. Gasoline vapors, when present, are outlined by a blue line.

events categorized as "near continuous vapor release" happened in vehicles manufactured after the rollout of ORVR. Without Stage II vapor recovery, the population is not protected from emissions arising from the so-called legacy fleet without ORVR, vehicles with deteriorating ORVR, or motorcycles and boats, both of which do not have ORVR.

Of particular importance for public health and policy is the ability of ORVR systems to (1) reduce exposure to gasoline vapors during refueling to a safe level, and (2) continue to function at a high level over the lifetime of a vehicle. This is important for two reasons. First, volatile organic compounds (VOCs) released during refueling can chemically react in the atmosphere, contributing to ozone and other secondary pollutant formation, which can harm human health directly through cardiovascular pathways (14). ORVR systems are intended to reduce this potential, by preventing VOCs from escaping into the atmosphere where they can react with other species. Second, as previously discussed, exposure to primary VOCs, such as those in gasoline can also negatively impact health directly, from exposure during vehicle refueling. However, limited work has been conducted to test the assumption that ORVR reduces exposure to a "safe" level during vehicle refueling. In fact, it is unclear what a "safe" level of exposure to gasoline vapors is, particularly as there is not a standardized formula for gasoline.

Numerous studies have been conducted (15, 16) to characterize the potential harms of gasoline with specific formulas or additives, but these reports typically compare different formulas of gasoline rather than comparing exposure to no exposure. Evidence suggests that while exposure during refueling is likely, health effects from gasoline at infrequent low-levels may be small, although individual components are carcinogenic (15, 16). Conversely, evidence from occupational studies has shown that individuals chronically exposed to lower levels of gasoline vapors, for example gas station attendants, are at higher risk for certain cancers (17, 18). Despite this evidence, we do not fully understand what risk gasoline vapors pose to the general public during typical vehicle refueling, or the cumulative impact of such exposure over an individual's lifetime, particularly in today's regulatory environment. Our findings highlight, in a visually compelling manner, that individuals can be exposed to substantial amounts of gasoline vapors during refueling, even in a vehicle fleet saturated with ORVR.

Future studies are vitally needed to determine the risk to individuals during typical refueling sessions in a vehicle fleet saturated with ORVR, especially because exposure to gasoline is ubiquitous and occurs throughout the lifetime. We recommend comprehensive exposure assessments that estimate exposure, internal dose, and health effects, as well as real-time monitoring of volatile organic compounds, potentially using a portable SHED (19) deployed at a gas station and paired with an infrared camera optimized for gas imaging. In addition, we recommend future work to develop an algorithm for estimating the amount or concentration of vapors shown in video from an infrared camera, to provide a better understanding of the concentration of vapors dispersing around a station.

This pilot study has several limitations. First, a convenience sample of stations and vehicles were used, and thus may not be representative of the true vehicle fleet in NYC. However, ORVR saturation in our sample was fairly close to an estimate for all registered vehicles in New York State and City (94 vs. 81%). It is additionally reassuring that both these estimates are above the EPA estimate of 71% for ORVR saturation in the older 2012 US fleet (8) and that the saturation in our convenience sample is above New York State's modeled estimate of 85% or greater for the older 2013 fleet (20). The median manufacturing year of our sample was consistent with that for New York State and City's registered vehicles (median = 2013). Second, the small sample size does not provide ample power for statistical tests. Third, vehicle make, model, and age were estimated by researchers and therefore there is potential for misclassification. Finally, real-time estimates of VOC concentrations were not obtained.

CONCLUSIONS

In an ORVR saturated vehicle fleet, use of an infrared camera optimized for VOC imaging allowed for the identification of vapor sources, viewing vapor trajectory and dispersion, and identifying the timing of vapor release during refueling. In this pilot study, 14 out of 16 observed refueling events resulted in vapor emissions, with severity varying substantially by vehicle make/model and age. A full exposure-assessment incorporating infrared cameras, quantitative monitors, and biologic samples is needed to understand exposure to and health effects of fuel vapor at gas stations, in an ORVR saturated vehicle fleet.

DATA AVAILABILITY STATEMENT

All datasets generated for this study are included in the article/**Supplementary Material**.

AUTHOR CONTRIBUTIONS

MH and JS conceptualized the study and completed data collection. JS wrote the first manuscript draft and completed initial data analysis. MH supervised and reviewed all the data analysis and edited the manuscript. All authors agree to be accountable for the content of this work.

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SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fpubh.2020.00018/full#supplementary-material

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2021 Study

Benzene emissions from gas station clusters: a new framework for estimating lifetime cancer risk

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RESEARCH ARTICLE

Benzene emissions from gas station clusters: a new framework for estimating lifetime cancer risk

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Abstract

Purpose During gas station operation, unburned fuel can be released to the environment through distribution, delivery, and storage. Due to the toxicity of fuel compounds, setback distances have been implemented to protect the general population. However, these distances treat gasoline sales volume as a categorical variable and only account for the presence of a single gas station and not clusters, which frequently occur. This paper introduces a framework for recommending setback distances for gas station clusters based on estimated lifetime cancer risk from benzene exposure.

Methods Using the air quality dispersion model AERMOD, we simulated levels of benzene released to the atmosphere from single and clusters of generic gas stations and the associated lifetime cancer risk under meteorological conditions representative of Albany, New York.

Results Cancer risk as a function of distance from gas station(s) and as a continuous function of total sales volume can be estimated from an equation we developed. We found that clusters of gas stations have increased cancer risk compared to a single station because of cumulative emissions from the individual gas stations. For instance, the cancer risk at 40 m for four gas stations each dispensing 1 million gal/year is 9.84×10^{-6} compared to 2.45×10^{-6} for one gas station.

Conclusion The framework we developed for estimating cancer risk from gas station(s) could be adopted by regulatory agencies to make setback distances a function of sales volume and the number of gas stations in a cluster, rather than on a sales volume category.

Keywords Gas station clusters · Cancer risk · Benzene · VOC emissions · Air pollution modeling

Introduction

In 2016, about 143 billion gallons of gasoline were dispensed at United States (US) gas stations [1]. This is equivalent to an average consumption of 442 gal of gasoline per person [2]. During the operation of a gas station, unburned fuel is released from multiple sources, including spills, leaky pipes, leaky dispenser hoses, leaks in underground storage tanks, and underground storage tank venting [3–6]. All of these sources of exposures can contribute to negative health effects due to the toxicity of chemicals in unburned fuel.

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Gasoline contains the BTEX group, consisting of benzene, toluene, ethylbenzene and xylenes, all of which are toxic [7–9]. Within the BTEX group, benzene is the sole chemical classified as a human carcinogen [10]; it is a causal agent of leukemia and is associated with non-Hodgkin's lymphoma and multiple myeloma [7, 11]. While the general population experiences low exposure to benzene at gas stations when dispensing gasoline, at-risk populations include those who are occupationally exposed, people that live near gas stations, and children in schools near stations [12–16]. People living near gas stations can be exposed to chemicals from the stations even inside their homes, as modeled by Hicklin et al. [17] in Malta and measured by Barros et al. [18] in Portugal. Additionally, studies suggest that there may be a risk of childhood leukemia associated with living close to gas stations [19–22]. Yet another study concluded that the lifetime cancer risk at and around selected gas stations in Iran exceeded values proposed by the US Environmental Protection Agency (EPA) [23].

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As cancer risk due to toxic evaporative emissions from a gas station is a function of distance from the gas station [24, 25], regulations in the form of setback distances have been put in place to protect people. In the US, different states have different guidelines for setback distances, and even within states different counties may set their own guidelines. Based on estimations of lifetime cancer risk, the California Air Resources Board (CARB) recommends that new sensitive land uses (such as schools and daycares) should not be sited within 300 ft (91 m) of a large gasoline dispensing facility, where large is defined as having a sales volume of at least 3.6 million gallons per year [26, 27]. On the other hand, a county council in the US state of Maryland approved a zoning amendment that requires gas stations that pump more than 3.6 million gallons of gas per year to be 500 ft. from public and private schools, parks, playgrounds, recreational areas, homes, and environmentally sensitive areas [28]. In these examples, sales volume is treated as a categorical value, which results in a loss of precision and assumes the relationship between exposure and cancer risk is the same for all sales volumes in a given category. Moreover, we are unaware of any setback distances that account for the presence of gas station clusters. To improve regulations around setback distances for gas stations, the effects of sales volume and number of gas stations in a cluster on cancer risk due to fuel spills and evaporative fuel losses should be examined.

To inform recommendations for setback distances from gas stations, we performed air dispersion modeling to obtain the spatial distribution of lifetime cancer risk due to benzene emissions from single gas stations and clusters, making assumptions about evaporative emission rates from gas stations and meteorological conditions that are representative of Albany, New York. The main objectives of this paper are to (1) examine how lifetime cancer risk due to evaporative benzene releases depends on sales volume and the number of gas stations in a cluster and (2) to introduce a framework for recommending setback distances between gas stations and adjacent sensitive land uses based on estimated lifetime cancer risk from benzene exposure. Unlike previous work [24, 26], this framework treats sales volume as a continuous variable, accounts for cumulative emissions from gas station clusters, and allows calculating cancer risk by evaluating an equation instead of reading it from a plot.

Methods

Meteorological data

We used three years of hourly meteorological data (2015–2017) for Albany, New York in the US. A location in the state of New York was chosen, because we wanted our work to be relevant to a local community. We chose Albany over New York City, however, because New York City has generally much taller buildings, which would need to be accounted for in pollutant dispersion simulations, something that is typically avoided when modeling health effects from generic gas stations [24, 29]. The surface air data were obtained from the National Climatic Data Center for the Albany International Airport, and the upper air data were obtained from the NOAA/ESRL Radiosonde Database for Albany, NY [30]. Descriptive statistics of the meteorological data were obtained with the 'openair' package in R 3.5.1 and are shown in Supplementary Table 1, and the wind rose is shown in Supplementary Fig. 1.

Generic gas station modeling

We assumed that gas station clusters consist of up to $N_{st} = 4$ gas stations located on the four corners of an intersection (even though other configurations are possible). Figure 1 depicts the four-gas station configuration. Each of the four gas stations is assumed to have four pump islands, from which fuel can be dispensed from both sides. At each gas station, the underground storage tank vent pipe is assumed to be in the center of the gas station, even though they are often located at the fence line or on the walls of convenience stores or auto repair shops, which are often part of a gas station. For configurations with more than one gas station, the origin of the modeling domain is the center of the intersection. For a single gas station configuration, the origin is the center of that gas station. This assumption was made for better comparability between the cancer-distance relationships for single and clusters of gas stations. Figure 2 depicts three-, two-, and one-gas station configurations. In Figs. 1 and 2, the origin is indicated by a red plus sign.

Air dispersion modeling

To model the dispersion of benzene vapors released into the atmospheric environment through evaporative losses from gas station clusters, we used AERMOD and AERMET, regulatory software developed by the US EPA [31, 32]. The AERMOD software models hourly levels of air pollutants in gas or particulate phase in the atmospheric boundary layer based on a steady-state plume approach that accounts for meteorological, topographic, surface roughness and emission source information [33]. AERMOD was compared to 16 tracer release field studies, and with few exceptions was found to have superior model performance when compared to other models tested [34]. The AERMET software was used to pre-process meteorological data for input into AERMOD. Benzene levels for subsequent cancer risk estimations were modeled on two-dimensional polar grids at different radial distances r_j (from 0 to 200 m in 20-m steps) and different angles φ_i (from 10° to 360° in 10° steps). Benzene levels were simulated at a 1-h temporal resolution at three elevations, $z = 0$, 2 and 4 m,

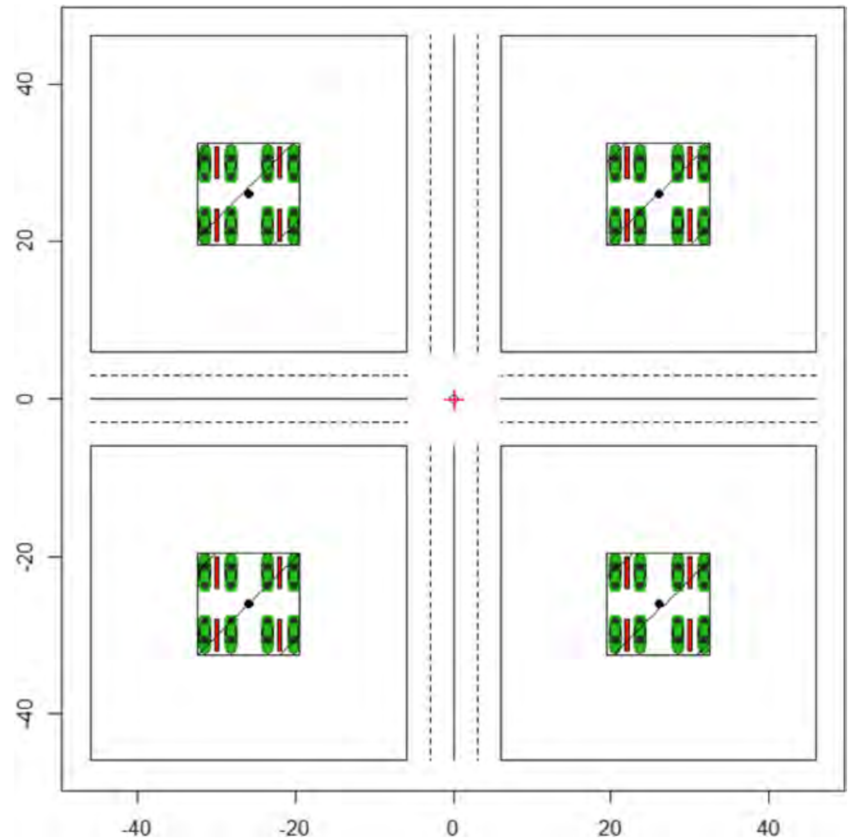

Fig. 1 Generic gas station cluster with one gas station on each corner of an intersection (drawn to scale except for enlarged vent pipes). Each gas station can accommodate two vehicles (green) per pump island (red) and has one vent pipe in the center (black dot). Diagonal lines indicate gas station canopies. Axes labels indicate distance in meters. The red "+" represents the origin of the modeling domain

representative of the ground-level, the breathing zone, and a second-floor level residence, respectively. We configured AERMOD to calculate the 3-year temporal averages of the hourly time series of the simulated concentration fields. For visualizing the simulated 3-year average benzene levels, much finer numerical grids that were particularly well resolved around the benzene sources were used to create contour plots of benzene levels using Matlab™ R2017b version.

Emission modeling

Emissions of unburned gasoline from gas stations depend on installed pollution prevention technologies. We assumed presence of pollution technology that is representative or will become representative for most US states (with the notable exception of California). Based on these assumptions, we simulated California Air Pollution Control Officers Association's (CAPCOA) Scenario 5B ("Phase I" with vent valves, underground storage tank) [24].

Specifically, we assumed presence of Stage I vapor recovery, which reduces the amount of fuel vapors that would be pushed into the atmosphere during the refueling of underground storage tanks by the rising fuel levels in the tanks by directing these vapors into tanks on the delivering tanker truck. We assumed the absence of Stage II vapor recovery, because EPA has recently allowed states not to require Stage

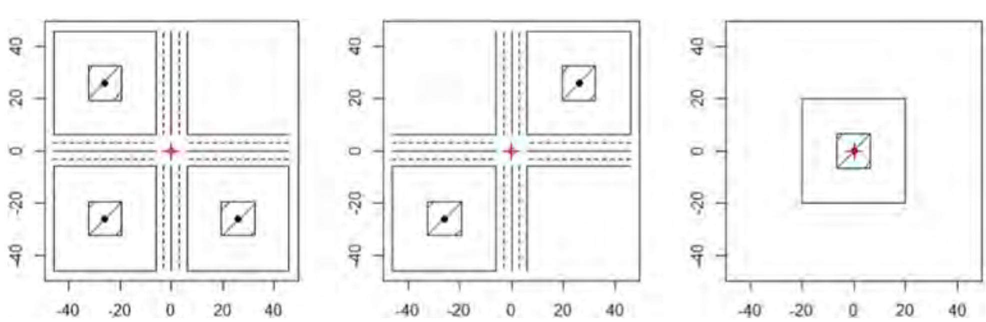

Fig. 2 Simplified depictions of generic gas station clusters consisting of three, two and one gas stations (drawn to scale except for enlarged vent pipes). Each station has one vent pipe in the center (black dot). Diagonal lines indicate gas station canopies. The red "+" represents the origin of the modeling domain. Axes labels indicate distance in meters

II systems if widespread use of Onboard Refueling Vapor Recovery (ORVR) is given [35].

The refueling emission factor we used accounts for the fact that not all vehicles (e.g., legacy fleet, motorcycles) are equipped with ORVR. We assumed an ORVR penetration rate (PR) of 93.2% which represents the percentage of gasoline dispensed to ORVR-equipped vehicles that has been estimated for the US for the year of 2019 [35]. We assumed 95% for the efficiency of ORVR [35], i.e., refueling losses from ORVR-equipped vehicles are 5% of the losses from non-ORVR equipped vehicles, which is 8.4 lbs./kgal. Thus the refueling loss is given by: $[(1 - PR) + 0.05 \times PR] \times 8.4$ lbs./kgal = 0.96 lbs./kgal. Table 1 summarizes the emission losses we assumed.

To convert gasoline losses into benzene emission rates, we made assumptions about fuel composition. We assumed that current US liquid gasoline (except in California) contains about 1% of benzene by volume [36]. Like CAPCOA [24] and Hilpert et al. [29], we assumed a mass fraction of benzene in the ullage/headspace of the underground storage tank of 0.003 (by weight benzene in vapors) [29].

Emission factor values were used to calculate the parameter values for the AERMOD input file. For a 1-gas station configuration, we defined a total of nine sources: one vent pipe, four refueling and hose permeation loss sources (combined for each pump island), and four spillage loss sources (one for each pump island). We think of a gas station as having point and volume sources. Refueling, hose permeation and spillage losses were modeled as volume sources because they do not occur at fixed locations since the locations of different customer vehicles vary even if the same pump is used for refueling. For all volume sources, we assumed an initial lateral dimension of 3.02 m (stated as SYINIT in Table 2) and initial vertical dimension of 1.86 m (stated as SZINIT in Table 2), which are based on previous modeling assumptions for gas stations. The release height (stated as HS in Table 2) of the spillage losses was assumed to be at the ground-level elevation, because spilled droplets fall to the ground, where most of the evaporation takes place, while the release height for refueling and hose permeation was assumed to be 1 m. Vent pipe losses were modeled as point sources because underground storage tank vent pipes extend up above the surface of the pavement behaving more like a chimney emission rather than a volume emission. For vent pipe sources, the altitude from the ground was assumed to be 4 m (stated as HS in Table 2). For each gas station, all emission sources were assumed to be located at its center. Table 1 describes the source parameters.

Table 1 Emission factors

Type	Loss (lbs/kgal)*
Loading	0.084
Breathing	0.21
Refueling for 0% ORVR penetration	8.4
Refueling for assumed 93.2% ORVR penetration	0.96
Spillage	0.61
Hose permeation	0.062

*In the US, regulatory agencies typically express emission losses in units of lbs./kgal, i.e., pounds of gasoline emitted/lost per 1000 gal of gasoline dispensed

Note that 1 lbs./kgal = 0.1198 kg/m^3 *

Table 2 shows selected input parameters for AERMOD simulations. Note that the SYINIT (initial lateral dimension of the volume source [SYINIT]) of 3.02 m was obtained by dividing the canopy width (13 m) by 4.3, a constant, which is based on previously developed modeling assumptions for gas stations [24]. The vent pipe exit velocity was calculated from the sales volume SV_{single}, the assumed inside diameter of the vent pipe (2 in = 5.1 cm), and the loading and breathing emission factors from Table 1.

Our single generic gas station was assumed to have a sales volume SV_{single} = 1,000,000 gal/yr. Even though the dependence of stack exit velocity on sales volume causes simulated benzene concentration fields to depend non-linearly on sales volume, this non-linearity is negligible. A comparison between the concentration field simulated for the actual stack exit velocity and the field for a hypothetical stack exit velocity of zero showed that concentrations differed by no more than 0.3% on the numerical grid points. Therefore, concentration fields for other sales volumes can be estimated from the simulations for SV_{single} = 1,000,000 gal/yr by assuming a linear scaling law between the benzene concentration field for SV_{single} = 1,000,000 gal/yr and the actual sales volume. Finally we assumed no buildings to be present and flat terrain.

Cancer risk modeling

Cancer risk (CR) from inhalation exposure to benzene was modeled using the concept of Inhalation Unit Risk (IUR), which is an estimate of the increased cancer risk from inhalation exposure to a concentration of 1 μg/m^3 for a lifetime [37]. EPA estimates IUR to be between 2.2×10^{-6} per μg/m^3 and 7.8×10^{-6} per μg/m^3 [37]. Lifetime cancer risk from benzene was calculated according to EPA guidelines for inhalation risk assessment [37]. Thus, cancer risk at each point of the numerical grid can be calculated as follows:

$$CR = IUR\ x\ EC \quad (1)$$

where EC (μg/m^3) is the spatially variable exposure concentration or intake. The intake is calculated from EC = (CA x ET x EF x ED) / AT where CA (μg/m^3) is the benzene concentration modeled at each grid point and averaged over the entire

Table 2 Selected input parameters for AERMOD simulations

Description	Emission rate QS (g/s)	Release height HS (m)	Stack exit emperature TS (Kelvin)	Exit velocity VS (m/s)	Stack diameter DS (cm)	Initial lateral dimension of volume SYINIT (m)	Initial vertical dimension of volume SZINIT (m)
Hose permeation losses and refueling losses combined	0.0001567	1.0	N/A	N/A	N/A	3.02	1.86
Spillage losses	0.0003159	0.0	N/A	N/A	N/A	3.02	1.86
Vent pipe loading and breathing losses combined	0.0001522	4.0	290	0.001236	5.1	N/A	N/A

Abbreviations: *N/A* not applicable

simulation period (3 years), ET (hours per day) is the exposure time, EF (days per year) is the exposure frequency, ED (years) is the exposure duration, and AT (hours) is the average time per exposure period. We chose EPA's upper bound for IUR which would be appropriate for a sensitive land use and exposure parameters indicative of constant presence e.g. children in a boarding school or residents in a nursing home: ET = 24 h/day, EF = 350 days/year (7 days/week × 52 weeks/year), ED = 70 years (lifetime cancer risk), and AT = 613,200 h (70 years × 365 days/year × 24 h/day) [37]. We therefore calculated the lifetime cancer risk as follows: $CR = 7.8 \times 10^{-6}\ (\mu g/m^3)^{-1}$ x EC.

To facilitate estimation of cancer risk of the various gas station clusters as a function of distance r from the gas station and the total sales volume $SV_{tot} = N_{st}\ SV_{single}$ where N_{st} represents the number of gas stations, we fitted a simple mathematical model to the spatial distribution of modeled cancer risk. This model condenses the concentrations simulated on the two-dimensional polar grid onto a one-dimensional grid where concentration is expressed as a function of distance r from the origin of the model domain: $\langle CR \rangle \left(r_j\right) = \frac{1}{N}\sum_{i=1}^{N} CR \left(r_j, \varphi_i\right)$ where $N = 36$ is the number of discrete angles used in the numerical grid. We assumed that the dependence of cancer risk $\langle CR \rangle$ on distance r is described by an exponentially decaying function according to the following equation:

$$\log_{10}\left(\langle CR \rangle \frac{10^6 \mathrm{gal/yr}}{N_{st}\ \ SV_{single}}\right) = a + br \tag{2}$$

As shown in Section A in Supplementary Material, Eq. (2) is consistent with empirical Gaussian plume models [38].

Also note that the cancer risk scales linearly with sales volume SV_{single}, consistent with the AERMOD simulations, which yields concentration fields that scale linearly with benzene source terms. Therefore, regressions coefficients a and b do not depend on which value of SV_{single} is chosen in the simulations. We also assumed cancer risk to depend linearly on N_{st}; however, a and b can be expected to show some dependence on N_{st} because benzene levels at any grid point do not scale exactly linearly with N_{st} as the gas stations in the cluster have typically different distances to a grid point. We therefore did not only determine a and b by fitting simultaneously the modeled spatial distributions of cancer risk for all gas station configurations to Eq. (2), but we also determined for each gas station configuration alone a and b and then used one-way ANOVA to examine potential differences between regression coefficients among the four gas station configurations (significance level of 0.05). The goodness of fit was evaluated with the R^2 value. In the regressions, we excluded the first two data points for distances 0 and 20 m from the regressions, because inclusion would have increased the variance of the regression too much since for these distances normalized cancer risks were too different across the four cluster types.

Cancer risk modeling and analyses were completed using R 3.5.1 (R Foundation for Statistical Computing, Vienna, Austria).

Results

Air pollution modeling

Figure 3 shows simulated atmospheric benzene levels arising from the gas station cluster, which contains four gas stations, for three different elevations. Generally, benzene levels decrease with distance from each gas station until the influence of one of the other three gas stations is felt; then levels may increase again. Further away from the intersection and the entire gas station cluster, benzene levels generally decrease. Benzene level fields do not exhibit any symmetry, and levels are not constant along circles of radius r around the center of the modeling domain.

Close to the intersection (< 60 m), benzene levels depend substantially on elevation. At the 4-m elevation around the vent pipes, the only modeled point sources of benzene, concentrations tend to be highest. Further away from the intersection (>80 m), benzene levels do not depend much on elevation.

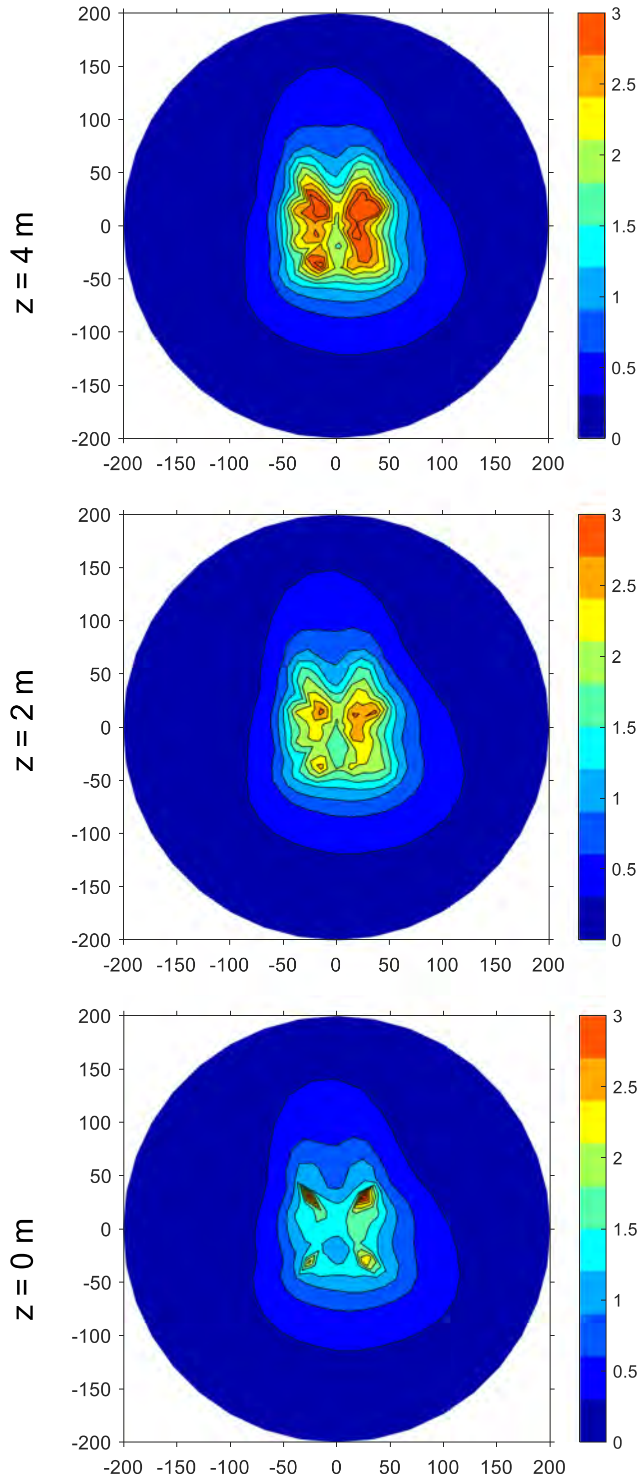

Fig. 3 Modeled atmospheric benzene levels (3-year average) due to emissions from four-gas station configuration shown at 3 elevations: 0 (bottom panel), 2 (middle panel), and 4 m (top panel). Abscissa and ordinate labels indicate distance in meters. Color bar indicates benzene concentration in μg/m^3

Figure 4 shows simulated atmospheric benzene levels in the breathing zone that arise from the four different gas stations clusters. Benzene levels clearly depend substantially on the number of gas stations present. Moreover, the spatially dependent concentration fields for more than one gas station cannot simply be obtained by multiplying the concentration field for one gas station by the number of gas stations in the cluster.

Cancer risk modeling

Figure 5 shows boxplots of the log-transformed cancer risk normalized by total sales volume (left-hand-side of Eq. (2)) as a function of distance from the origin of the modeling domain. For distances ≥40 m, median normalized cancer risks are roughly the same for the four configurations. For distances <40 m (0 and 20 m), however, these risks differ substantially between configurations. Specifically, the single gas station exhibits different patterns, with cancer risk monotonically decreasing with distance; whereas for the configurations with more than one gas station cancer risk is greatest at a distance of 20 m. The heights of the box plots (interquartile range) in Fig. 5 also illustrate that cancer risk for a given distance and gas station configuration can vary by more than a factor of 10 depending on the angle φ_i.

Figure 6 shows the linear regressions for the log-transformed cancer risk medians, normalized by total sales volume, for the four different gas station configurations. Results from the regression analyses are summarized in Table 3. For all regressions, R^2 values are >0.96, and the F statistics are statistically significant ($p < 0.05$). In addition, all intercept and regression coefficients are statistically significant ($p < 0.05$), meaning distance and lifetime cancer risk are significantly associated. One-way ANOVA showed that regression coefficients a and b are not different across the four gas station configurations. At the same time, confidence intervals (CIs) between coefficients across gas station configurations overlapped. CIs of the regression coefficients that account for the data of all gas station configurations together overlap with the CIs from the four individual regressions.

Summary and discussion

Spatial dependence of benzene levels

We for the first time presented simulations for the cumulative effects of several gas stations on atmospheric benzene levels. As previously established, benzene levels depend substantially on distance from gas station [12–15, 25]; however, similar to Hilpert et al. [29], we also found that elevation is a determining factor [29]. Benzene levels on the ground surface (0-m elevation) and in the breathing zone (2-m elevation) are similar to each other (Fig. 3), because at lower elevations benzene levels arise from volume and surface forces and are not affected much by vent pipe emissions. Close to a gas station (<

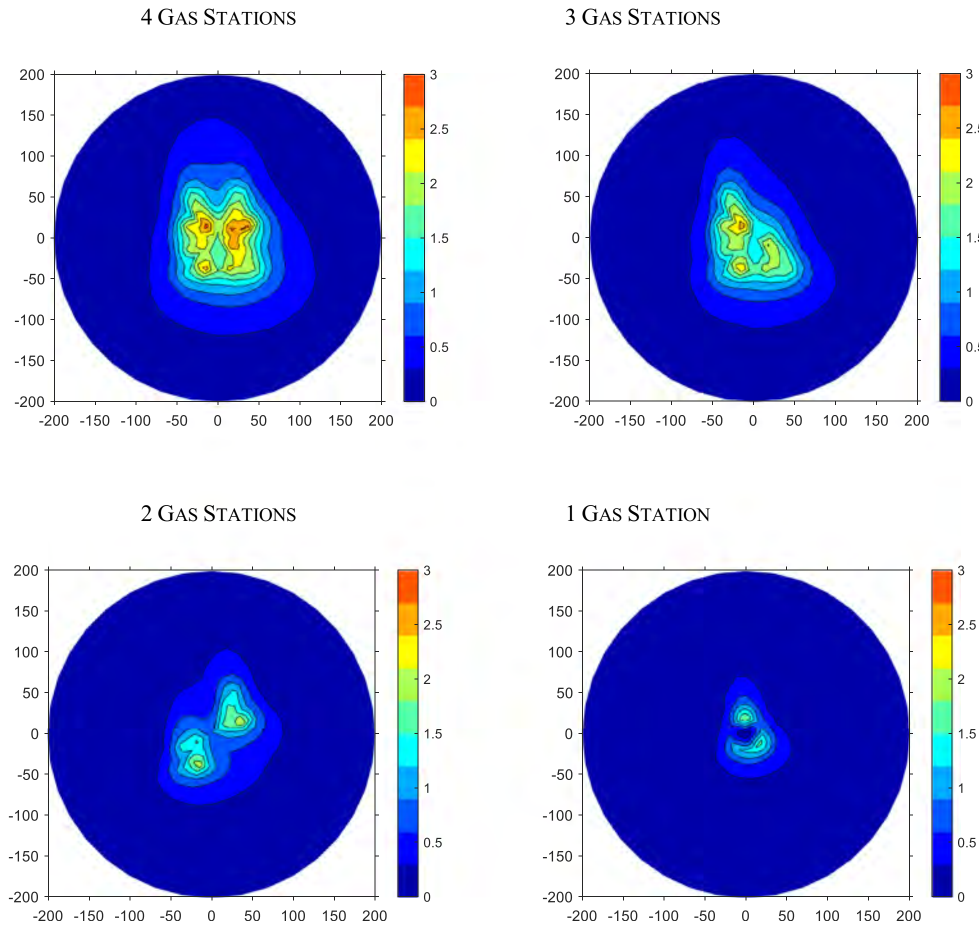

Fig. 4 Modeled atmospheric benzene levels (3-year average) due to emissions from 4, 3, 2, and 1 gas station configuration at an elevation of 2 m. Abscissa and ordinate labels indicate distance in meters. Color bar indicates benzene concentration in μg/m^3

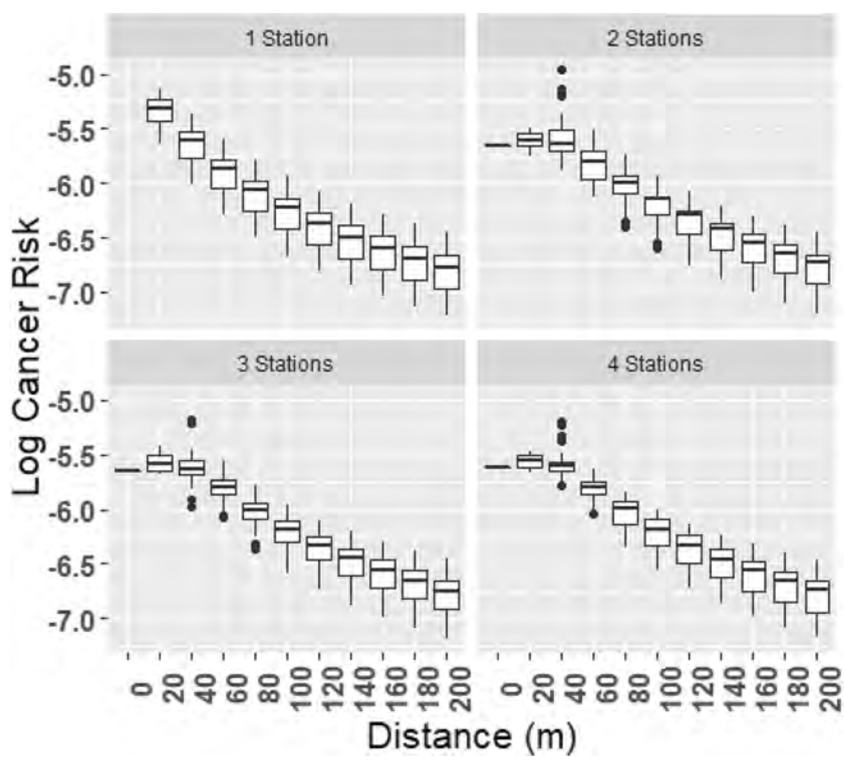

Fig. 5 Lifetime cancer risk <CR> normalized by total sales volume and then log-transformed for four different gas station clusters consisting of 1, 2, 3 and 4 gas stations by distance r from the origin of the model domain. Box plots indicate the variation of cancer risk at distance r due to its dependence on the angle φ_i at the $z = 4$ m elevation

Table 3 Summary of linear regression for medians of lifetime cancer risk according to Eq. (2)

# Gas Stations	All	4	3	2	1
Intercept *a* [95% CI]	−5.50 [−5.55, −5.45]	−5.40 [−5.53, −5.28]	−5.42 [−5.53, −5.30]	−5.41 [−5.51, −5.32]	−5.45 [−5.61, −5.30]
Distance coefficient *b* (1/km)* [95% CI]	−6.49 [−6.91, −6.07]	−7.12 [−8.10, −6.15]	−7.04 [−7.92, −6.15]	−6.92 [−7.62, −6.22]	−7.03 [−8.19, −5.87]
R-squared	0.96	0.98	0.98	0.99	0.97
Cancer Risk at 40 m	N/A	9.84×10^{-6}	6.94×10^{-6}	4.66×10^{-6}	2.45×10^{-6}

*All intercepts and distance coefficients are statistically significant ($p < 0.05$)

40 m), benzene hot spots are present at a 4-m elevation where the vent pipes of the fuel storage tanks were assumed to release fuel vapors to the atmospheric environment, potentially putting residents at the 2nd floor level at risk. Further away from the center of the modeling domain (about >80 m), concentration fields do not depend much on elevation, as evidenced by the almost identical contour lines for benzene levels. This is because of vertical mixing of the benzene vapors due to atmospheric dispersion. Additionally, for quality assurance, we conducted a simulation for a single gas station where stack velocity is zero and compared the benzene concentration levels to our results (which use a stack velocity of 0.0012). We found that the percent difference for benzene concentration between the two simulations was close to zero.

Cancer risk as a function of sales volume and number of gas stations

We performed for the first time analyses that not only allow estimating cancer risk of a single gas station as a function of sales volume but also the risk from multiple gas stations in a cluster. In contrast, previous reports presented examples of cancer risk as a function of distance *r* only from a single gas station in the form of plots for a given sales volume SV, with no guidance about how to estimate cancer risk for a different sales volume. See, for example, Appendix E in CAPCOA [24] which presents cancer risks for gas stations dispensing 1 million gal/yr or Figs. 1, 2, 3, 4, 5 and 6 in CalEPA/CARB [26] for a gas station dispensing 3.6 million gal/yr [24, 26]. Our plots and Eq. (2), both of which normalize cancer risk by sales volume, respond to this need. For instance, one can now easily answer the question: what is the lifetime cancer risk <CR> of a single gas station dispensing 10 million gal/yr at a distance $r = 150$ m? We can read from the red line in Fig. 6, that $\log_{10}(\ldots) \sim -6.5$ and therefore $10^{-6.5} = (\mathrm{CR})\,\frac{10^6\,\mathrm{gal/yr}}{N_{st}\;\;\mathrm{SV}_{single}}$. Since $N_{st} = 1$ and $\mathrm{SV}_{\mathrm{single}} = 10^7$ gal/yr, the cancer risk is $\langle \mathrm{CR} \rangle = 10^{-5.5}$ which is 3 in a million.

Directional dependence of cancer risk

At a single location (specified by distance *r* and angle φ_i), substantial differences between the cancer risk inferred from Eq. (2) and the risk calculated from Eq. (1) using the AERMOD benzene concentration at that location may occur.

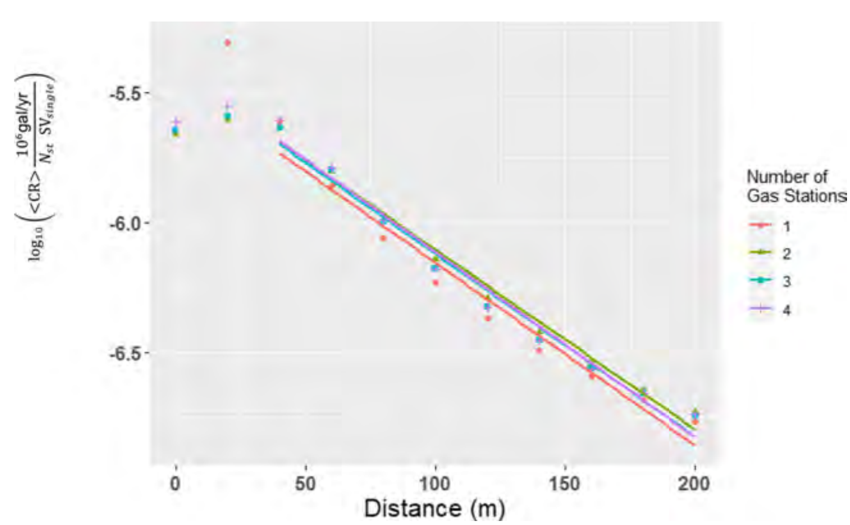

Fig. 6 Linear regression of the medians of lifetime cancer risk <CR> normalized by sales volume and then log-transformed for 1, 2, 3 and 4 gas stations. The regression excludes the first two distances (0 and 20 m)

This is because Eq. (2) represents a cancer risk averaged over all angles φ_i and because cancer risk may vary by more than an order of magnitude depending on φ_i for a given r (Fig. 5). Local meteorology and in particular variability in wind direction partially explain the spatial patterns and the directional dependence of modeled benzene concentrations, as a comparison between the wind rose (Supplemental Fig. 1) and the benzene concentrations fields (Figs. 3 and 4) shows. Therefore while Eq. (2) provides insights about how cancer risk depends on distance from gas station(s), detailed air dispersion simulations may be required to evaluate cancer risk for given receptor locations.

Equation for calculating cancer risk from gas station clusters

We proposed a simple equation, Eq. (2), which is based on an exponentially decaying function for estimating cancer risk as a function of distance from a gas station or a cluster of gas stations. Our statistical analysis (p-values and R^2) showed that cancer risk is a function of distance from gas station(s). Based on a theoretical premise, modeled cancer risk could be expected to scale linearly with sales volume SV_{single} but it was not clear whether it would also scale linearly with the number of gas stations N_{st}. One-way ANOVA, however, supports the hypothesis that cancer risk (averaged over all angles φ_i) scales linearly with total sales volume $SV_{single}\ N_{st}$ for distances ≥40 m as evidenced by the similarity of the normalized cancer risk plots for the four different gas station configurations (Fig. 5) and the regression analyses for Eq. (2). However, Eq. (2) should not be used outside the range of distances r used to inform the regression (40 to 200 m).

As an example for an application of Eq. (2), we use it to calculate cancer risk at a distance r = 150 m from the aforementioned gas station dispensing 10 million gal/yr. With $a = -5.5$ and $b = -6.5\ \text{km}^{-1}$, $\log_{10}(\ldots) = a + b\ r = -5.5 - 6.5 \times 0.15 = -6.5$, the same value determined from Fig. 6, thus also resulting in a cancer risk of 3 in a million.

Setback distances

Our Eq. (2), or variations thereof that account for actual emission rates and local meteorological conditions, provides a framework for formulating setback policies. E.g., if policy makers assume $CR = 5 \times 10^{-6}$ is an acceptable cancer risk, one can solve Eq. (2) for r to calculate the distance at which this cancer risk is obtained, e.g., for a cluster of $N_{st} = 4$ gas stations having each a sales volume SV_{single} = 3.6 million gal/year (or a single gas station dispensing 14.4 million gal/year): $r = \left[\log_{10}\left((\text{CR})\frac{10^6 \text{gal/yr}}{N_{st}\ \ \text{SV}_{single}}\right) - a)\right] / b$ = 145 m. This distance can be interpreted as a setback distance, keeping in mind that cancer risk varies due to its directional dependence. This setback distance is much greater than the setback distance of 91 m recommended by CARB for California gas stations (with much lower emission factors) dispensing more than 3.6 million gal/year [26]. Thus, CARB guidelines should be used with caution if vapor emission control technology is below their standards.

Policy recommendations

While it is not surprising that cancer risks are higher for gas station clusters than for a single gas station, some policies on setback distances for gas stations account only for emissions from a single gas station [26], thereby neglecting the cumulative cancer risk arising from a cluster. We propose that policies should acknowledge the additional cancer risks arising from gas station clusters. This issue is of concern when a new gas station is built in an area where none is initially present and additional gas station(s) might be proposed thereafter or when a new gas station is built close to an existing one. Furthermore, our findings could provide a basis for improved standardization of policy at both the county and state level. Finally, we recommend that setback distances account for actual sales volume.

Limitations

Our study has some limitations. While we have devised an approach for estimating cancer risks from a gas station cluster, our study is not representative of any specific gas station development, because we only accounted for one set of meteorological conditions, assumed flat terrain, and made assumptions about fuel composition (benzene content) and emission prevention technology that are only representative of the US (except California). Indeed, according to an article published by the International Fuel Quality Center in 2009 benzene levels in gasoline can reach up to 7% in regions where these levels are regulated [39]; and levels can perhaps be even higher where not regulated. Moreover, benzene level may vary seasonally due to changes in fuel composition (winter versus summer fuel) [40–42] . However, because EPA [36] estimates of national gasoline benzene content (~ 1% by volume in 2016) and prior studies inform our assumptions, we feel they are a reasonable proxy. We also used emissions factors, which potentially underestimate actual emissions, as shown in a recent study that measured vent emissions at two fully functional US gas stations, finding that emissions greatly exceeded the emission factors listed in the CAPCOA (1997) study [24, 29].

Conclusions

We have developed a model to estimate cancer risk from gas station clusters, accounting for the increasing risk with additional gas stations and allowing for continuous rather than categorical sales volume inputs. Overall, we found that clusters of gas stations result in increased cancer risk compared to a single station. For instance, the cancer risk at 40 m for four gas stations each dispensing 1 million gal/year is 9.84×10^{-6} compared to 2.45×10^{-6} for one gas station. This framework can be utilized in real-life scenarios as a basis to estimate cancer risk by distance for gas station clusters in the US. Future work should consider developing a more general and widely applicable equation for cancer risk that also accounts for site-specific information such as emission factors, benzene content of the liquid gasoline and the gas phase in the ullage of the storage tank, and summary statistics of meteorological conditions. Future policies around setback distances should be reassessed to account for heightened risk from clusters.

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s40201-020-00601-w.

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Data availability All data and material are publicly available.

Compliance with ethical standards

Conflicts of interest/Competing interests The authors declare they have no conflict of interest.

Code availability Code available upon request.

Ethics approval This study does not involve human subjects.

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2021 Study
An Analytical Framework for Evaluating Potential Truck Parking Locations

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An Analytical Framework for Evaluating Potential Truck Parking Locations

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Abstract

As the number of trucks on the road continues to increase, mandatory rest periods combined with a decreasing number of parking spaces and amenities geared towards truck drivers have created a paradoxical yet often overlooked issue of truck parking shortage. Especially within the urbanized landscape of New Jersey, truck stops are rarely considered as the highest and best use form of development and those that exist are often expensive to operate. Most of the existing research on this issue has focused on parking demand modeling or applications of the intelligent transportation system technology to improve the use of existing truck stops. Nonetheless, limited previous research has focused on expanding truck parking capacity. This study develops a methodological framework for evaluating some of the important social, economic, and environmental factors when planning the development of a new truck parking facility. With an example application to the State of New Jersey, this study presents a step-by-step analytical process to help prioritize potential truck parking locations. The results will be useful to develop a practical tool that can be utilized by the private and public sectors involved in addressing regional freight parking capacity shortfall and safety concerns.

Keywords: truck parking; location analysis; cost-benefit analysis

1. Introduction

The United States is experiencing continued growth in commercial vehicle travel on national roadway systems and while facing critical shortages in truck parking facilities. In addition, new federal legislation on hours-of-service (HOS) for truck drivers requires a maximum of 70 hours of driving within a week and a 30-minute break during the first eight hours of a shift. In areas with congested freight operations and inadequate parking facilities, a fatigued driver may continue to drive long distances seeking for parking on highway shoulders, thereby introducing safety and environmental hazards. As such, there is a pressing need to strategically expand or develop existing or new truck parking facilities.

As one of the largest consumer markets and a national gateway for freight movements, the State of New Jersey is experiencing substantial increase in freight traffic and correspondingly, truck parking demand. The North Jersey Transportation Planning Authority has laid the groundwork for identifying the need for additional truck parking in Northern New Jersey area. According to their two-phase studies (Federal Highway Administration, 2012a; Federal Motor Carrier Safety Administration, 2015), more than 80% of the 34 observed truck parking facilities in the region were over capacity, and almost 100% more parking spaces were needed to meet the demand in 2006. In view of growing freight traffic, the gap between parking space demand and supply is expected to widen in the years to come.

To help regional planners evaluate the social, economic, and environmental factors associated with truck parking site selection and facility development, this study investigates a semi-quantitative methodological framework that accounts for these factors. In line with the strategic development of freight infrastructure, the proposed framework can be a practical tool that provides decision makers with engineering guidelines and economic insights for alleviating congestion, facilitating compliance of the HOS requirement, and reducing the safety hazards. By attempting to highlight some of the more important factors to consider when developing truck parking site selections, this framework paves the way for more detailed and relevant cost-benefit analyses. Building upon the premise of a traditional environmental impact analysis, our methodology expands to include economic and safety factors and integrate the most relevant quantitative modeling approaches from existing literature, thus serving as the foundation for more detailed cost-benefit analyses.

This paper is organized as follows. Section 2 reviews previous research related to the development or expansion of truck parking facilities. Section 3 presents a framework to systematically integrate most important factors related to the truck parking location decision. Section 4 illustrates the methodology through a numerical example of a candidate truck stop site in the State of New Jersey. Section 5 summarizes principal research findings and proposes future research directions.

2. Literature Review

Many studies conducted by metropolitan planning organizations (MPOs) and state departments of transportation (DOTs), such as Federal Highway Administration (2012a), Federal Motor Carrier Safety Administration (2015), North Jersey Transportation Planning Authority (2008, 2009), Delaware Valley Regional Planning Commission (2011), Office of Intermodal Project Planning (2001), and Minnesota Department of Transportation (2010), have highlighted a deficit in truck parking that is expected to increase over the next decade. Federal Highway Administration (2012a), Federal Motor Carrier Safety Administration (2015), and North Jersey Transportation Planning Authority (2008) have used a parking demand model developed in Pécheux et al. (2002). Although funding for expanding parking capacity is available, competition and priority issues among other freight and transportation projects along with limited availability make it a challenging and often overlooked problem. For example, a 2014 survey amongst over 4,000 stakeholders identified the parking problem only as the 6th (out of 10) most critical issue facing the trucking industry (Transportation Research Board, 2003). Those funding sources and their associated challenges were detailed by the United States DOT (Federal Highway Administration, 2012b).

Research into possible mitigating solutions has primarily focused on intelligent transportation system technology in the form of interconnected, dynamic parking systems where capacity data can be transmitted directly to the truck drivers through electronic message signs, text message alerts, GPS devices, or radio (I-95 Corridor Coalition, 2009). The I-95 Corridor Collation (2015) has developed a plan for the implementation of such technologies coupled with certain increases in parking capacity, marketing tactics, development of future sustainability plans and the coordination of multiple MPOs and state DOTs across the Northeast and Mid-Atlantic Corridor. Additional mitigation strategies have focused on the commercialization debate and the need for public-private partnerships. The United States DOT recommended the use of public-private partnerships (Federal Highway Administration, 2012b).

While many previous studies called for expanded capacity, only one study included a methodology for site selection that could be used across regional boundaries. Caltrans and the Alameda Contra Costa County Medical Association looked at 33 sites and qualitatively rated them according to various characteristics, ranging from accessibility to economic impact (The Tioga Group, Inc., 2008). Whereas the previous work relies on a qualitative rating scale, this study aims to develop a semi-quantitative methodology by quantifying and where possible, effectively monetizing the social, economic, and environmental consequences associated with developing or expanding any truck stop.

Transportation based cost-benefit methodologies have been the topic of multiple sources (Lewis and Currie, 2016; Litman and Doherty, 2009; Xu and Lambert, 2015). With regards to the development of truck stops, such insights have been very limited. The complete quantification of the social, economic, and environmental costs and benefits associated with developing truck stops is a challenging task due to the lack of data and proper methodologies, each of which requires a separate research effort. Thus, instead of focusing on such cost-benefit methodologies, the purpose of this review is analyzing the previous research highlighting relevant factors to be considered in the truck stop development. As an initial exploration, this research will lead to a larger cost-benefit analysis research regime for freight infrastructure expansion.

3. Methodology

This section is composed of five parts, beginning with an examination of the different data sets and techniques employed throughout the paper. Next, demand estimation, safety analysis, economic and environmental methodologies are explained, along with individual analyses of how future studies and research into these topics should be conducted. Such factors are visualized in Figure 1. Each of these methodologies is additionally employed in the numerical case study in Section 4.

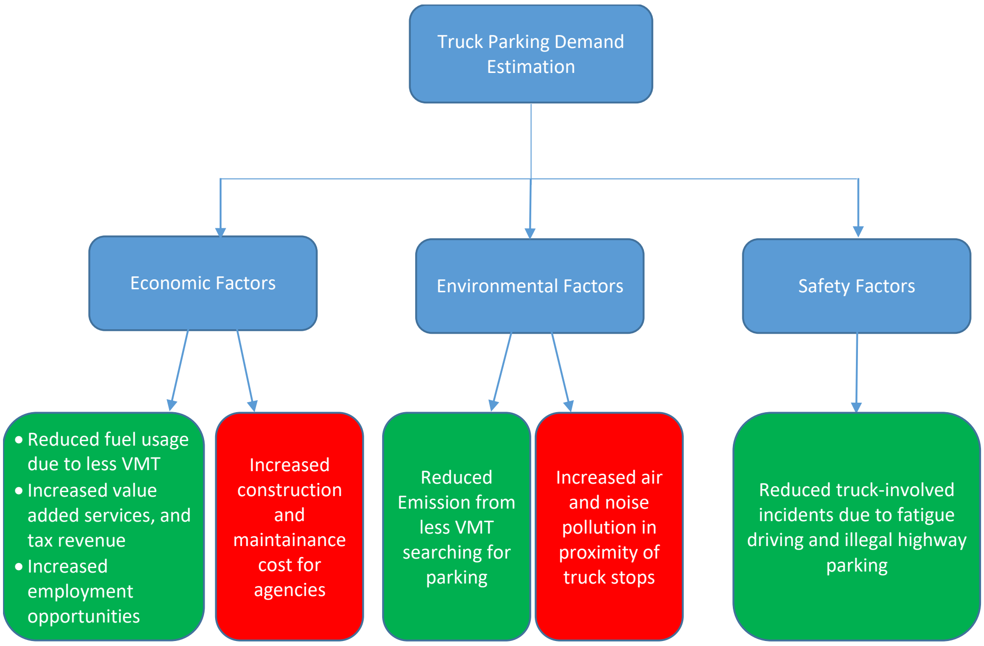

Figure 1. Flow chart of the proposed methodology.

3.1 Data Sources

Demand modeling uses equations and parameters developed by Pécheux et al (2002). Data related to economic and fiscal factors was gathered from Reference USA (2014), a database commonly used for business and consumer research. Truck stops and related businesses are listed under the Standard Industrial Classification (SIC) code 554103. In order to determine economic indicators on a per parking space and per acre basis, multiple datasets from TruckStopGuide.com (2014) were downloaded and compiled. Tax records obtained from New Jersey Transparency Center (2015) were utilized to determine fiscal indicators for each parcel, as part of the economic methodology. The air pollution and noise data and their effects on property values is based on hedonic regressions performed by Chay and Greenstone (2005) and Palmquist (1980). The safety data were obtained from the Plan4Safety New Jersey Crash Database, developed by the Rutgers University Center for Advanced Infrastructure and Transportation. This database records detailed highway crash accident information, but it has not yet been fully geocoded. In this research, the database was utilized to estimate greenhouse gas reductions and analyze safety statistics associated with shoulder-parked and fatigued driver truck-related accidents at the highway corridor level. Lastly, air and noise pollution spatial modeling equations widely used in both academic and professional case studies have been applied in this study. Regulations for noise pollution emission and mitigation standards are in accordance with the Federal Highway Administration (2011) and New Jersey Department of Transportation (2011), respectively.

3.2 Truck Parking Demand Estimation

Before any analysis can be conducted, demand for truck parking is an important consideration in the planning process. In order to estimate truck parking demand at a specific location, this research employed the model developed by Pécheux et al (2002) and added several parameters according to the results from Delaware Valley Regional Planning Commission (2011). Rather than basing the demand for parking on the characteristics of a parking facility, the model predicts truck parking demand for a highway segment based on the total truck hours of travel and the time and duration of stops.

3.3 Safety Factors and Site Selection

As a major driver of developing highway truck stops, safety is an important factor in the context of site selection. Through the analysis of the New Jersey Plan4Safety Crash Database, it was found that approximately 400 accidents involving parked trucks and 10 accidents involving fatigued truck drivers have occurred in New Jersey in 2015. Furthermore, most of them are found to take place on the New Jersey Turnpike/Interstate 95 corridor of the State as shown in Figure 2. Therefore, this corridor, especially within its most heavily congested sections, would represent a candidate location for truck parking in New Jersey. Further research can be conducted to associate crash risk with truck-parking-related factors (Gates et al. 2013).

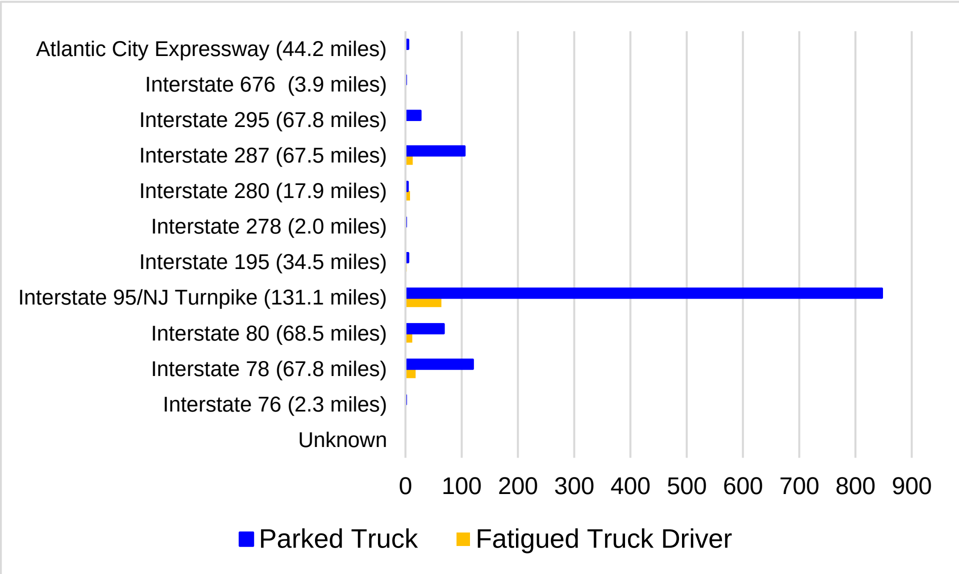

Figure 2. Number of accidents by New Jersey Interstate Highways (2003-2015).

3.4 Economic Analysis

To date, there are no known studies analyzing the economic impacts of truck stops. Recent work suggests that general rest stops bring economic benefits in the form of reduced excess driving, construction business, business and employment opportunities, tax revenue and value added services for commercial truck stops, as well as traveler comfort and tourism promotion; however, quantification of these benefits can be difficult (McArthur et al., 2013). This section quantifies possible benefits based on truck stop data in New Jersey.

In total, 86 locations containing long-term parking for trucks were identified within the State. Among them 29 locations were privately owned gas stations and 26 locations were missing significant data on TruckStopGuide.com (2014) datasets. Therefore, those sites were omitted, leaving a total of 31 applicable truck stops, which were broken down as 5 single-service and 26 full-service rest areas. Single-service rest areas solely provide fuel, restrooms, and overnight parking, while full-service rest areas additionally include available services such as food and repair shops.

Table 1 compiles economic averages for single-service and full-service truck stops in New Jersey. Of those full-service rest areas, 9 locations were identified as being larger than 15 acres in size. These larger rest areas are separately analyzed, as larger truck stops would help to reduce truck parking shortages and be more attractive to private investors. The decrease in job density for larger full-service truck stops can be attributed to most of the associated acreage being devoted to parking, where even as the number of parking space increases, the number of amenities and services provided will remain constant.

Table 1. New Jersey truck stop economic indicators.

	Total Parking Spaces	Total Acreage	Spaces per Acre	Aggregate Number of Employees Needed	Jobs per Acre
Single-Service Truck Stops	89	19.48	4.57	37 to 85	1.90 to 4.36
All Full-Service Truck Stops	2,208	364.75	6.05	564 to 1,298	1.55 to 3.56
Large Full-Service Truck Stops (15+ Acres)	1,682	280.95	5.99	315 to 740	1.12 to 2.63

Using the same datasets analyzed for the economic methodology (TruckStopGuide.com, 2014) along with the New Jersey tax records (New Jersey Transparency Center, 2015), the fiscal methodology attempted to analyze payroll, sales and property tax totals for the different breakdowns of the 31 rest areas. This information for 2014 is presented in Table 2.

Table 2. Fiscal data for existing New Jersey truck stops in 2014.

	Single-Service Truck Stops	All Full-Service Truck Stops	Large Full-Service Truck Stops (15+ Acres)
Payroll Volume & Tax (1%)			
Total Payroll	$3,300,000 - $11,600,000	$23,250,000 - $61,250,010	$10,750,000 - $37,500,000
Total Payroll Tax	$33,000 - $116,000	$232,500 - $612,500	$107,500 - $375,000
Payroll per Acre	$169,405 - $595,483	$63,742 - $167,923	$38,263 - $133,475
Payroll Tax per Acre	$1,694 - $5,954	$637 - $1,679	$382 - $1,335
Sales Volume & Tax (7%)			
Total Sales	$30,000,000 - $70,000,000	$502,000,000 - $1,695,000,000	$213,000,000 - $745,000,000
Total Sales Tax	$2,070,000 - $4,900,000	$35,140,000 - $118,650,000	$14,880,000 - $5,215,000
Sales Volume per Acre	$1,510,000 - $3,590,000	$1,380,000 - $4,650,000	$760,000 - $2,650,000

Sales Tax per Acre	\$110,000 - \$250,000	\$100,000 - \$330,000	\$50,000 - \$190,000
Property Tax			
Total Net Property Value	\$4,496,100	\$91,494,700	\$57,110,500
Total Prior Year Tax Amount (2014)	\$111,104	\$1,615,245	\$836,793
Net Property Value per Acre	\$230,806	\$250,843	\$203,276
Prior Year Net Tax Amount per Acre	\$5,704	\$4,428	\$2,978

The table shows there are notable differences in the per acreage values of each tax. The high payroll and property tax per acre efficiency for single-service rest areas can be attributed to a larger portion of such properties being devoted to revenue generating usage while larger full-service truck stop acreage will likely be devoted to actual non-revenue generating spaces, i.e., parking. The variations for payroll and sales volume taxes can be attributed to the fluctuations in the number of employees. Property tax on the other hand is solely based on the property specifics and is independent of total employees or sales volume, resulting in a specific figure for this category. Per-acre figures are utilized numerical example calculations in Section 4 to estimate revenues as a result of proposed truck parking development.

3.5 Environmental Factors and Analysis

Utilization of existing methods of spatial air and noise pollution measurement is proposed as a means of estimating the environmental impacts of developing a new truck stop, particularly to the neighborhoods.

3.5.1 Air Pollution Analysis

Although this study assumes that there will be no net increases in air pollution as a result of expanded truck parking, increased particulate concentrations in and around truck stops are expected to negatively affect nearby property values. It is estimated that every 1-$\mu g/m^3$ increase in total suspended particulates results in a 0.05% decrease in property values and vice-versa (Chay and Greenstone 2005). Precise reductions in air quality to the adjacent properties can be estimated using the Gaussian plume modeling equation (Stockie, 2011) shown in equation (1).

$$C(X, Y, 0) = [Q/(\Pi \times u \times \sigma_y \times \sigma_z)]\ EXP[(-H^2)/(2 \times \sigma_z^2)]\ EXP[(-Y^2)/(2 \times \sigma_y^2)] \quad (1)$$

Where

C = Concentration at some specific point or receptor (grams per meters cubed)

Q = Source pollutant emission rate (grams per second)

Π = Pi

u = Horizontal wind velocity along plume centerline (meters per second)

σ_y & σ_z = Horizontal & Vertical dispersion coefficients (meters)

H = Effective plume stack height (meters)

Y = Downwind perpendicular distance (meters)
X = Downwind distance at which C is calculated (meters)

Given the flat terrain of New Jersey, the Z-coordinate is assigned a value of 0 since ground level is the most relevant in the case of analyzing emission levels of nearby properties. Note that horizontal and vertical dispersion coefficients vary based on downwind distance and atmospheric conditions. See Plume Dispersion Coefficients (2014) for a table providing these values. In order to fully utilize the Gaussian plume equation (1), a truck stop which consists of numerous individual point sources is considered as a single point source with plumes being emitted from the center of the truck stop.

3.5.2 Noise Pollution Analysis

Increases in noise pollution are inevitable in such a case where dispersed idling trucks are centralized into the new or expanded truck stops. This methodology takes into account the projected increases in noise as well as commonly implemented noise abatement criteria using the following basic equation:

Net Noise Pollution = Increase in Noise Level at Truck Stop – Noise Abatement Implementation

Changes in noise levels at the new or expanded truck stops can be computed through the following equation (2), while changes in sound level over distance is presented in equation (3) (Occupational Safety and Health Administration, 2014):

$$\Delta L = 10 \log_{10} n \tag{2}$$

Where ΔL = the decibel level increase and n = the number of equal sound sources.

$$2d = L - 6 \text{ dBA} \tag{3}$$

Where d = the distance from the sound source and L = the decibel level in dBA.

As the distance from the sound source is doubled, noise levels decrease by 6 dBA (Federal Highway Administration, 2011). Mandated by the Federal Highway Administration, maximum noise levels for large trucks are not to exceed 85 dBA 50 feet away. Combined, this data can be used to approximate sound values over different distances. For every 2.5 dBA increase in noise levels above 55 dBA, residential property values are assumed to decrease by 0.2% to 1.2% with wealthier communities, containing higher willingness to pay for peace and quiet, being more sensitive to such increases in noise pollution (Palmquist, 1980). Any truck stop development project will require a noise impact study that evaluates the feasibility of installing noise barriers to remediate the noise pollution problem. Specific noise remediation guidelines are determined by state, and municipal factors and those guidelines used by the New Jersey DOT based on existing land use are accessible via the website (New Jersey Department of Transportation, 2011).

4. Case Study in New Jersey

4.1 Site Selection

In this section, the proposed methodology has been applied to evaluate a 200-space, 46.76-acre parcel in Newark, New Jersey, identified by the North Jersey Transportation Planning Authority as a site of interest for a new truck stop. The site is along one of the busiest sections of the Interstate 95/New Jersey Turnpike Corridor. As Figure 2 shows, this is also on the corridor where the most truck-related accidents take place. A 30,000 square foot facility is also proposed, which would include a convenience store, multiple meal options, and maintenance facilities, in addition to a fueling station. Since the focus of this study is the methodology integration and development, the case study serves as an application example for illustration purpose.

Located on Hyatt Avenue in the Ironbound District of Newark and consisting of 5 separate parcels, the currently vacant site is just down the road from Port Newark and Port Elizabeth Marine Terminal and other related industrial sites. The site is situated between Interstate 95 and US 1-9, which also acts to separate it from any residential or noise-sensitive areas, which is especially useful in noise pollution evaluations. Additional nearby points of interest include the Interstate 95 and Interstate 78 junction and Newark Liberty International Airport. The site and surrounding areas are visualized in Figure 3.

Figure 3. Case study site location within Newark, New Jersey.

4.2 Parking Demand Analysis

The truck parking demand estimation formulas and associated model parameters in Pécheux et al. (2002) are applied to estimate the parking demand for each analysis segment. Regional Travel Model-Enhanced data is acquired from North Jersey Transportation Planning Authority to help select analysis segments with more than 1,000 trucks volume per day and provide traffic volume for conducting the demand model calculation. Additionally, the parking inventory of public rest areas and private truck stops for this segment were obtained given the distribution of truck parking facilities in New Jersey. The results are as follows:

Site Factor – Truck Traffic along I-95 (New Jersey Turnpike)

Length (L, Bi-directed, from New York City to Philadelphia) = 343 km (213 mi)

Daily total truck volume (V_t) = 17,500 trucks per day

Speed limit (S) = 105 kph (65 mph)

Supply – Truck Parking Facilities along I-95 (New Jersey Turnpike)

$Parking_{RA}$ = 855 spaces

$Parking_{TS}$ = 1,489 spaces

Demand – Truck Parking Demand along I-95 (New Jersey Turnpike)

Segment truck travel time per trip (TT) = L/S = 343/105 = 3.27 hrs

Truck-hours of SH travel (THT_{SH}) = $P_{SH}\times V_t\times TT$ = (.36)(17,500)(3.27) = 20,601 veh-hrs

Truck-hours of LH travel (THT_{LH}) = $P_{LH}\times V_t\times TT$ = (.64)(17,500)(3.27) = 36,624 veh-hrs

Truck-hours of SH parking demand (THP_{SH}) = $THT_{SH}/12$ = 20,601/12 = 1,716 veh-hrs

Truck-hours of LH parking demand (THP_{LH}) = Parking time/Driving time×THT_{LH} + $THT_{LH}/12$

= 0.70×36,624 + 36,624/12 = 28,689 veh-hrs

Peak-hour parking demand for SH (PHP_{SH}) = $PPF_{SH}\times THP_{SH}$ = (.02)(1,716) = 34 veh

Peak-hour parking demand for LH (PHP_{LH}) = $PPF_{LH}\times THP_{LH}$ = (.09)(28,689) = 2,582 veh

SH and LH peak-hour parking hourly demand by facility type:

$PHP_{(SH,RA)} = P_{RA}\times PHP_{SH}$ = (.23)(34) = 8 veh

$PHP_{(SH,TS)} = P_{TS}\times PHP_{SH}$ = (.77)(34) = 26 veh

$PHP_{(LH,RA)} = P_{RA}\times PHP_{LH}$ = (.23)(2,582) = 594 veh

$PHP_{(LH,TS)} = P_{TS}\times PHP_{LH}$ = (.77)(2,582) = 1,988 veh

The total peak-hour parking demand for public rest areas is 8+594 = 602 trucks, and the total peak-hour parking demand for private truck stops is 26+1,988 = 2,014 trucks. Considering the supply of parking spaces on this segment, there is a surplus of public rest area parking of 855-602 = (+) 253 spaces, while there is a shortage of private truck stop parking of 1,489-1,988 = (-) 499 spaces. Hence, based on the predicted truck traffic volume and current truck parking spaces, we can forecast there will be a significant shortage of truck parking spaces in the near future along New Jersey Turnpike, which is the major freight route in New Jersey.

4.3 Economic Analysis

As described earlier, the economic analysis accounts for various factors. Based on this analysis the primary quantifiable factors are the anticipated number of jobs created and the associated increased in tax revenue.

Employment

The average of the 'average number of employees needed' figure for the large full-service truck stops of 1.875 jobs per acre (see Table 1) is used in the calculation herein. Considering the site area size of 46.76 acres, the estimated number of new jobs is 88 (1.875 jobs per acre×46.76 acres).

Revenue

The average value of revenue is used in this calculation (see Table 2). The total payroll is \$4,015,234 (\$85,869×46.76). The sales revenue is \$79,725,800 (\$1,705,000×46.76). The annual payroll tax is \$40,167 (\$859×46.76). The annual sales tax is \$5,611,200 (\$120,000×46.76). The annual property tax is \$139,251 (\$2,978×46.76).

4.4 Environmental Impacts Analysis

Recalling from the previous methodology section, air and noise pollution impacts from the truck stops are monetized based on their impacts on residential property values. In this case study, the truck stop is separated from residential areas by US Highway 1-9, which is a major truck route. On this route, a large portion of the noise pollution can be ameliorated since the traffic on the highway will produce more noise. To demonstrate the methodology, our calculations will assume that the proposed truck stop has a direct effect on property values in the neighboring Ironbound neighborhood of Newark.

Gaussian Plume Dispersion Modeling to Determine Impact on Property Values

Step 1: Assumptions

- A single emission source consisting of 200 trucks in 0.7 km (2,300 feet) from residential neighborhood.
- Plume stack height of 4.2 meters, approximately the average height of a large truck tractor trailer.
- Downwind (u) of 4.7 mph (2.1 m/s) at transverse distance (Y) of 100 m (Stockie, 2011).
- σ_y and σ_z values of 48 m and 24 m based on neutral atmospheric conditions (Plume Dispersion Coefficients, 2014).

Step 2: Utilization of Gaussian Equation

The Gaussian Plume model is applied with the following values for each variable:

Q (measured in micrograms) = 0.014×10^6 µg/s

u = 2.1 m/s downwind

σ_y & σ_z = 48 m & 24 m, respectively

H = 4.2 m

The given numerical values for all variables are applied in equation (1) and C = 1.02 $\mu g/m^3$ per parking space could be calculated. This figure is multiplied by 200 to get the total emissions experienced in 0.7 km (2,300 feet) and thus 204 $\mu g/m^3$ are obtained for 200 parking spaces. Lastly, this figure is multiplied by 0.05%, representing the decrease in property values per $\mu g/m^3$ of pollution. The final result, 10.2% decrease in property values, is the approximate reduction in residential property values closest to the truck stop based on NO_X emissions coming from parked trucks at the proposed site.

Estimated Noise Pollution Impact on Nearby Property Values

Step 1: Assumptions

- Noise levels adhering to the maximum allowable federal guidelines.
- A single sound source consisting of 200 trucks in 0.7 km (2,300 feet) from residential neighborhood.
- To show the entire methodology, disregard adjacent highways between truck stop and residential areas, which would produce much higher dBA levels than truck stop.

Step 2: Estimation of Impacts on Property Values

Considering there are a total of 200 trucks (n), the ΔL in equation (2) is computed as 23 which is added to 85 dBA to represent the maximum allowable noise level at 50 feet from any truck, yielding a total of about 108 dBA at a 50 feet distance from the approximate center of the truck stop. Using the distance-based exponential decay equation, the dBA level at 2,300 feet can be estimated at about 75 dBA.

Step 3: Assessment of Noise Abatement Strategies

As identified in the methodology, every 2.5 dBA increase in noise levels above 55 dBA results in anywhere from 0.2% to 1.2% reduction in property values. Given the characteristics of the Ironbound neighborhood of Newark, a value of 0.5% could be appropriate. The percentage reduction in property values due to the noise generated from the truck stop (without application of noise abatement criteria) has been calculated as 4% since there are 8 step reductions given 2.5 dBA threshold.

5. Conclusions

As part of freight system development, strategic expansion of truck stops is expected to not only improve mobility of the freight industry and reduce freight cost, but also boost local and regional employment and revenue opportunities, and thereby increase a region's long-term economic competitiveness. This study presented guidelines for truck parking site selection and outlined some of the major social, economic, and environmental factors associated with developing or expanding truck stops. The framework and its application to empirical case studies can provide useful insights to both public and private agencies into addressing regional parking capacity shortfall and safety concerns. The case study shows that certain factors of a truck stop development or expansion are more impactful to society than others. For example, sales tax proves to be the most lucrative source of revenue to the state government. On the other hand, society appears to be directly affected by air pollution to a much greater extent than noise pollution by means of significantly larger reductions in residential property values.

Future research is suggested as follows. Additional research is needed to investigate the truck parking deficit problems faced by New Jersey and many other states. As New Jersey's commercial industrial economy continues to thrive, distribution centers and other similar facilities will continue to remain the highest and best uses for the dwindling available industrial space, with truck stops receiving little consideration. Therefore, decision makers need to find a strategy to provide long-term truck parking space at the highest and best use sites such as distribution centers or warehouses. For example, sustainable methods of providing truck parking space, such as increasing the profitability of truck stops as ventures for the private and public sectors, could be possible. Such a strategy will require careful policy development along with strong and sustained cooperation between states and multiple private sector companies.

6. Acknowledgement

This research was funded by the Center for Advanced Infrastructure and Transportation (CAIT), a USDOT-designated University Transportation Center (DTRT13-G-UTC28). However, all the views and analyses in this document are of the authors.

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John sterrett

From: Dan Sonsedek ·
Sent: Monday, November 28, 2022 2:47 PM
To: John sterrett
Subject: Fwd: Fw: Truck soot
Attachments: DEF.docx

John,
Below are images of local truck stops showing spills that sit on the concrete and begin the runoff and seepage process that we all fear will contaminate our wells. Also attached are more supporting articles in which we as a community have gathered to help support that this truck stop should not be allowed to be built next to our homes.


Diesel
22


THORNTONS


Pilot

DEF (Diesel Exhaust Fluid)

DEF is corrosive to many materials, including carbon steel, copper, nickel, epoxy resins and aluminum.

"A panel of scientific experts convened by the World Health Organization's (WHO) International Agency for Research on Cancer (IARC) concluded in June 2012 that diesel engine exhaust is a Group 1 Carcinogen – that is, carcinogenic to humans".

https://www.ohsrep.org.au/diesel_-_declared_carcinogen

"Emissions from diesel engines contribute to the production of **ground level ozone** which damages crops, trees and other vegetations. Also produced is **acid rain,** which affects soil, lakes and stream and enters the human food chain via water, produce, meat and fish. These emissions also contribute to property damage and reduced visibility".

https://www.epa.gov/dera/learn-about-impacts-diesel-exhaust-and-diesel-emissions-reduction-act-dera

Three types of regeneration

Passive regeneration – is achieved when a diesel engine produces an exhaust temperature of 662 degrees Fahrenheit. Just by the exhaust reaching this temperature, soot trapped in the diesel particulate filter will be burned off.

Active regeneration – process happens automatically when the vehicle is in operation.

Manual regeneration – process only occurs when the vehicle is stationary. The parking brake must be set and the regeneration switch initiated by the vehicle's operator.

https://narsa-idea.org/2022/02/22/diesel-engine-regeneration-types-failures/#:~:text=Different%20Types,Manual%20regeneration

Diesel Particle Matter (DPM)

Levels of particulate pollution and elemental carbon (an indicator for diesel exhaust) are elevated near highways, especially those with high truck volumes. Research has shown children increased risk of asthma when exposed to traffic pollution.

Trucks also release dust from brake pads and pulverized tire rubber, adding to the particulate matter in the air. Studies of water sediment under bridges have found contamination from brake dust that contains asbestos, lead and other heavy metals. Truck air conditioning units and refrigerated containers commonly release refrigerants, which are green house gases

Driving Harm: Health and Community Impacts living near truck corridors

https://envhealthcenters.usc.edu/wp-content/uploads/2016/11/Driving-Harm.pdf

Small spills at gas stations could cause significant public health risks over time

Johns Hopkins Bloomberg School of Public Health

https://www.Sciencedaily.com/releases/2014/10/141007103102.htm

A study suggest that drops of fuel spilled at gas stations – which occur frequently with fill-ups – could cumulatively be cause long-term environmental damaged to soil and groundwater in residential areas in close proximity to the stations.

Over the lifespan of a gas station, concrete pads underneath the pumps can accumulate significant amounts of gasoline, which can eventually penetrate the concrete and escape into underlying soil and groundwater, potentially impacting the health of those who use wells as a water source. Conservatively, the researchers estimate, roughly 1500 liters of gasoline are spilled at the typical gas station each decade.

It is important that rain water does not flow over the concrete pads underneath the pumps. Otherwise, storm runoff contaminated with benzene and other harmful chemicals and can infiltrate into adjacent soil or form storm water that may end up in natural bodies of water.

According to our laboratory-based research and supported by our mathematical model, the assumption that a droplet of gasoline spilled onto the concrete will disappear, is incorrect.

Benzene emission from gas station clusters: a new framework for estimating a lifetime cancer risk.

Pei Yang Hsieh et al. J Environ Health Sci Eng. 2021

https://Pubmed.ncbi.nlm.nih.gov/34150235

Method – Using the air quality dispersion model AERMOD, simulated levels of benzene released to the atmosphere from a single and clusters of generic gas stations and the associated lifetime cancer risk.

Results – Cancer risk as a function of distance from gas stations (s) and total sales volume, shows that clusters of gas stations have increased cancer risk.

Conclusion – Adopt a regulatory agency to make setback distance a function of sales volume rather than sales volume category

Indiana Environmental Report

Lead researcher Markus Hilpert, associate professor of environmental health science at Columbia University.

https://indianaenvironmentalreporter.org/posts/gas-stations-emit-10-times-more-benzene-than-previously-recorded

"It turns out there are additional sources where unburned gasoline is released at gas stations. These are releases from storage tanks. These tanks have a vent pipe which releases the fuel vapors to the atmosphere once the tanks get over pressurized." This usually happens at night. These vents are integrated into the canopy, so you cannot even see them because they are really hidden.

Method – Using gas flow meters attached to the venting pipe and took measurements for three weeks.

Result – The chemical vapors released were about 10 times the amounts estimated by the California Air Pollution Control Officers Association's Industrywide Risk Assessment guidelines.

Conclusion – As this contaminant moves downwind, it spreads out and eventually it can reach the ground level. Emissions from gas stations were higher at night, potentially to exposing people to benzene while they sleep.

Hilpert and his colleagues discovered that vent pipes at gas stations released 10 times the amount of benzene than previously assumed in modeling used to determine how far gas stations should be placed away from sensitive sites like homes and schools. This research revealed that current regulations are insufficient to protect people from all the toxic chemical exposure near gas stations.

Water Resources Professional's Outreach Notebook Ground Water

By Stephen J. Vandas

U.S. Geological Survey

Denver Federal Center

Denver, CO 8225

https://pubs.usgs.gov/of/1994/0073/report.pdf

Water Resource Professional (WRP) includes individuals employed as hydrologists, engineers, hydrologic technicians, municipal-water and wastewater-treatment operators.

Water moves from areas of recharge to area of discharge through the saturated zone. Recharge areas are higher in elevation than discharge areas. Recharge, movement and discharge of the ground water are reflected in the elevation of the water table or potentiometric surface.

Surface water and ground water are integral to the hydrologic cycle. When surface water infiltrates the ground and percolates downward to the water table, it becomes part of the ground water system. If the surface water recharging an aquifer is polluted, it will become contaminated ground water. In addition, contaminated ground water can affect the quality of surface water at discharge areas.

Hydrologic Cycle and Ground Water

The hydrologic cycle is the constant movement of water above, on, and below the Earth's surface.

As rain falls, water begins to ***infiltrate*** into the ground. The infiltration rate in a paved area is almost zero. When and if the rate of precipitation exceeds the rate of infiltration, ***runoff,*** or overland flow, occurs.

Initially, the infiltrating water increases the soil moisture. When the soil is completely saturated, the additional infiltration ***percolates*** slowly down through the unsaturated zone to the saturated zone. This water recharges (adds) to the ground water in the saturated zone of the aquifer. Water in the saturated zone moves to area of ground-water discharge.

Gasoline Evaporative Losses from Retail Gasoline Outlets across Canada, 2009

http://www.gastationneighbors.org/reports/stats-canada.pdf

Retail gasoline outlets and their associated gasoline vapor emissions were selected in cooperation with the Environment Canada as an important data gap

Gasoline evaporative Losses

Sources of gasoline evaporative losses categories

1. Losses from standard operation processes and equipment of a retail gasoline outlet
    a. Storage tank losses (from working and breathing the storage tanks)
        a. Regular filling up of storage tanks by gasoline tanker trucks
        b. Losses due to changes of temperature and pressure
    b. Residual losses
        a. Losses due to typical ***daily*** leaks and spills
2. Losses from vehicles' own gasoline tanks while refueling

Leukemia rates high for kids living near gas stations

The globe and mail

Andre Picard

Published August 20, 2004

https://www.theglobeandmail.com/amp/life/leukemia-rates-high-for-kids-living-near-gas-stations/article20434890/

Research published in the journal Occupational and Environmental Medicine, provides powerful evidence that the common childhood cancer may be caused by exposure to the chemical benzene.

Jacqueline Clavel, a researcher at the French National Institute of Health and Medical Research in Villejuif.

The method: researchers examined the background of 280 children with acute childhood leukemia living in four large French cities.

Conclusion: the air around gas stations may actually be more polluted than in industrial settings. The scientists found that children living in proximity to gas stations and commercial garages were four times more likely to have developed leukemia. They were also most eight times as likely to have developed a specific from of the cancer, acute non-lymphocytic leukemia. The majority of children stricken by cancer were aged 2 to 6.

The longer a child lived near a gas station, the higher the risk, according to the study. The risk of developing leukemia increased by 3 percent per month, including time spent ***in utero***.

****The research did not reveal any increased cancer risk for children living in proximity to a host of other commercial and industrial enterprises such as plastic factories, printing plants, metal works and retail shops.

Gas Station Spills Could Pollute Water by Drips and Drops: Study

NBCNews.com

https://www.nbcnews.com/science/enviroment/gas-stations-spills-could-pollute-water-drips-drops-study-n221736

Published in the Journal of Contaminant Hydrology

Markus Hilpert, a senior scientist and associated professor in the department of health sciences at the John Hopkins Bloomberg School of Public Health. "People should be worried about the cumulative volume of gasoline that might infiltrate into the subsurface over the life of the gas station and that is aggravated by the fact that there is a trend to build bigger gas stations, ones that will sell 10 times the amount of gas sold in stations now."

John sterrett

From: Dan Sonsedek
Sent: Thursday, December 1, 2022 8:26 AM
To: John sterrett
Subject: Re: Water run off
Attachments: Epson_12012022082058 (1).pdf

John,
Attached below a letter from an expert witness regarding the effects of the truck stop on our property values.

Thank you.

--

To whom it may concern,

We are writing this letter on behalf of the residents that will be affected by the proposed truck stop gas station in West Chicago near the corner of North Avenue and Route 59.

We were asked our professional opinion as to if and how it would affect the values of the homes in the vicinity. In our combined 40 years of experience, this will surely negatively affect the home values by 10-15%.

From noise to smell, to air quality, and bright lights, all of these factors will be damaging to the nearby residents. It will take longer for these homes to sell and the number of potential buyers will be drastically reduced due to the location.

As history has always shown, the number one rule in real estate remains **location, location, location**. Buying real estate is the biggest financial investment a person will ever make. As a homebuyer, you depend on your home value to increase with the passage of time. This particular proposed truck stop will be a detriment to those who have already invested in their homes in the area.

If you need any additional information, we are happy to discuss this further.

Sincerely,

John + Beth

John & Beth Garry
The John Garry Team
Keller Williams Premiere Properties

John: 630.240.8085 **Beth:** 630.880.8085
John@JohnGarryTeam.com | JohnGarryTeam.com
45 S. Park Blvd. Suite 300, Glen Ellyn, IL 60137

City of West Chicago
Plan Commission/Zoning Board of Appeals
2023 Meeting Schedule

Tuesday, January 3, 2023
Tuesday, January 17, 2023

Tuesday, February 7, 2023
Tuesday, February 21, 2023

Tuesday, March 7, 2023
Tuesday, March 21, 2023

Tuesday, April 4, 2023
Tuesday, April 18, 2023

Tuesday, May 2, 2023
Tuesday, May 16, 2023

Tuesday, June 6, 2023
Tuesday, June 20, 2023

[1]Wednesday, July 5, 2023
Tuesday, July 18, 2023

Tuesday, August 1, 2023
Tuesday, August 15, 2023

[2]Wednesday, September 6, 2023
Tuesday, September 19, 2023

Tuesday, October 3, 2023
Tuesday, October 17, 2023

Tuesday, November 7, 2023
Tuesday, November 21, 2023

Tuesday, December 5, 2023
Tuesday, December 19, 2023

[1]*The first meeting of July will occur on Wednesday, July 5, 2023 due to Independence Day occurring the preceding Tuesday.*

[2]*The first meeting of September will occur on Wednesday, September 6, 2023 due to Labor Day occurring the preceding Monday.*

The Plan Commission/Zoning Board of Appeals meets the first and third Tuesday of each month.

Meetings start at 7:00 p.m.

Meetings will take place in the Council Chambers of West Chicago City Hall – 475 Street, unless otherwise indicated.

Packets are sent electronically no later than the Thursday prior to a meeting.

Notices for cancelled meetings will be sent as soon as practical.

The Plan Commission/Zoning Board of Appeals requires at least four members to be present to constitute a quorum.

If a member is not able to attend a meeting, the member should notify City staff as soon as practical.

For questions, please contact John Sterrett, City Planner, at 630-293-220 ext. 158 or at jsterrett@westchicago.org.