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Technical Note:
Evaluation of Potential Fuel Spillages at the Refueling Point during Mobile Refueling of Booster Inc.

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Disclaimer: This technical note does not necessarily represent the opinion of Columbia University.

Executive Summary

Key findings:

1. No spills to the ground below refueling points were observed during the 30 mobile refueling events examined.
2. The oil absorbing pad ("diaper"), which during nozzle transfer and during mobile refueling is wrapped around the dispensing nozzle, captures gasoline that otherwise would be spilled onto the ground. The drip mat underneath the refueling point serves as an additional fail-safe in case the diaper does not capture all spilled gasoline.
3. Gasoline masses captured by the diaper were significantly smaller than the masses of gasoline spilled during refueling at traditional gas stations.
4. During one out of 30 refueling events examined we observed a gasoline film on the body of the customer vehicle. The volume of that spill, however, was much smaller than the vehicle spills defined by CARB and gasoline did not reach the ground surface.

Significance:

1. The diaper effectively reduces if not eliminates gasoline spills onto the ground at the refueling point.
2. The smaller gasoline losses during mobile refueling result in fewer air toxics emissions (via gradual gasoline evaporation from the diaper) when compared to refueling losses at regular gas stations (via evaporation of spilled gasoline).
3. The diaper and drip mat could potentially be deployed at gas stations with gas station attendants to minimize refueling spills.

1. Background

1.1. Motivation

Booster Fuels, a San Mateo, California-based company, has developed an app-based service to refuel vehicle tanks with gasoline, a service which can be termed “mobile refueling.” Rather than rely on traditional gas stations, Booster delivers gasoline to the parked vehicles of its clients with a tanker truck, and Booster's trained professionals dispense the fuel. Booster’s business model does not rely at all on gas stations and their operation is therefore not associated with storage tank spills and potential groundwater contamination at gas stations.

While Booster’s model eliminates the potential for storage tank spills, there are still potential volatile organic compound losses that could potentially result in groundwater contamination. These losses could include gasoline spillage during client vehicle refueling, potentially resulting in contamination of pavement, soil, or groundwater by gasoline. Booster believes these spillages produce significantly less volume than those at gas stations, because the mobile refueling is performed by trained "Service Professionals" with proprietary equipment, which is well maintained. Moreover, Booster believes that even if losses occur, soil and groundwater contamination is significantly reduced, because their trained professionals seek to capture potential fuel spills using oil-absorbing pads ("diapers") that are wrapped around the dispensing nozzle and drip mats containing oil-absorbing pads that are placed underneath the refueling points.

Booster has reached out to Dr. Hilpert from the Columbia University Mailman School of Public Health to perform an independent study to compare the spillages from Booster’s mobile refueling to those at traditional gas stations. This technical note summarizes measurements and analyses of spillages that potentially occur below the refueling points during mobile refueling.

1.2. Results from the CARB Study

To compare the potential fuel spillages below refueling points during mobile refueling we measured to those at traditional gas stations, we used results from a study conducted by the California Air Resources Board (CARB).

In 1989 and 1990, CARB conducted a study to quantify gasoline spills occurring during the refueling of customer vehicles at California gas stations (Morgester et al. 1992). CARB examined spills at two different types of gas stations, a classification that still exists today: “vapor recovery gas stations” which are equipped with vapor recovery nozzles, and “conventional gas stations” which are not equipped with such nozzles. Since this study is performed in a region (Maryland and Washington DC) where conventional gas stations are prevalent, we present here only findings of the CARB study that are relevant to conventional gas stations.

CARB measured spills during four different refueling phases: 1) pre-fueling when the nozzle is removed from the dispenser and then inserted in the film pipe of a vehicle tank, 2) the fueling (refueling) phase, 3) the shut-off phase, and 4) the post-fueling phase. Furthermore, CARB distinguished between measurable spills ("M" spills) and vehicle spills ("V" spills). **Table 1** shows the total volume of spilled gasoline that occurred during each of the four phases for the 1,496 refueling events CARB examined. To standardize these results, we show in Table 1 also the average spill volume per refueling event for each of the four phases and for all four phases together.

Table 1: Spill volumes measured by CARB for conventional gas stations.

Refueling phase	Spill type	Spill volume of all refueling events (mL)	Spill volume per refueling event (mL)
Pre-fueling	M spill	65	
	V spill	12	
	M + V spill	77	0.05
Fueling	M spill	1,662	
	V spill	38	
	M + V spill	1,700	1.14
Shut-off	M spill	3,563	
	V spill	210	
	M + V spill	3,773	2.52
Post-fueling	M spill	328	
	V spill	150	
	M + V spill	478	0.32
All phases	M + V spill	6,028	4.03

Next, we summarize some key statistical measures, to which we compared the measurements we made:

- For gas stations not equipped with vapor recovery nozzles, CARB examined 1,496 refueling events. The average spill volume per refueling event was 4.03 mL.
- Assuming a gasoline density of 0.73 g/mL, the average spill mass per refueling event was 2.9 g.
- The fraction of refueling events with measurable spills was 16.6% where measurable means that the spill volume exceeded 1 mL.

2. Methods

2.1. Measurement rational

Measurements were performed to characterize potential gasoline spills occurring during mobile refueling and to quantify them as much as possible within the constraints of this study. Specifically, we 1) avoided substantial modification of the mobile refueling workflow, because such modification could have altered the nature and magnitude of potential spillages; and 2) did not spill any gasoline onto the ground at the refueling sites (like in CARB study where gasoline was spilled to derive a relationship between spill volume and the measured imprint of a spilled droplet) to avoid soil or groundwater contamination.

To characterize potential gasoline spills at the refueling points, two types of measurements were made:

1. Ground spillage observations: We carefully performed a visual observation of the refueling process at the refueling point to document potential gasoline spillages onto the ground (see Section 2.3 for details).
2. Spills captured by diaper: By weighing the diaper before and after refueling, we determined the mass of gasoline captured by the diaper (see Section 2.4 for details).

While the first measurement directly documents actual spillage potentially causing soil and groundwater contamination, this is not the case for the second measurement. Rather than actual spillage, the second measurement quantifies spills onto the ground that would occur if both the diaper and drip mat had not been used during mobile refueling (assuming the diaper does not affect the amount of spilled fuel). Thus, the measurement quantifies captured spills. This measurement is informative in two ways:

- It allows drawing conclusions about the working condition of the refueling equipment. Good working conditions would minimize actual spills should any of the safeguards (diaper and drip mat) partially or completely fail. Thus, comparison of the observed captured spill mass per refueling event to CARB's measured refueling spill mass at gas stations allows assessing the environmental impact of the hypothetical event in which the diaper and drip mat do not capture any spilled gasoline.
- They provide an upper bound for the evaporative gasoline losses that gradually occur from the diaper and spill mat (some of the gasoline will remain in the hydrophobic pads) after a spill capture. Quantifying these losses is important, because evaporated fuel contains air toxics. Since evaporative losses also occur from gasoline spilled at gas stations, comparing the captured spill mass per mobile refueling event to the spill mass per gas station refueling event allows comparing air toxics emissions of the two refueling approaches.

We also intended to measure the mass of potentially spilled gasoline captured by the drip mat. However, the mass balance approach we developed for quantifying spills captured by the diaper could not be extended to the drip mat, because the drip mat could accumulate materials other than spilled gasoline to a much greater extent than the diaper, because the drip mat was laid onto the ground.

Due to the Covid-19 pandemic, site visits were conducted by Columbia University with only one study team member. Due to the lack of a second study team member, full attention could be given to only one of the two measurements described above during a refueling event. Therefore, it was decided to either carefully visually observe and document all refuelings at a given mobile refueling site, or to measure the potentially spilled gasoline captured by the diaper during all refuelings.

2.2. Hypotheses

Based on an initial visit by Dr. Hilpert of the Booster operations in Maryland, the following two hypotheses were formulated:

Hypothesis 1: The captured spill mass during mobile refueling is smaller than the 2.9 g spill mass measured by CARB at self-service gas stations.

Hypothesis 2: The spill frequency during mobile refueling spills is smaller than the 16.6% spill frequency measured by CARB for refueling at self-service gas stations.

2.3. Ground spillage observations

Study personnel carefully observed the refueling processes at the refueling points, to detect the occurrence of potential gasoline spillage, including but not limited to droplets spilled onto the ground and spills of gasoline on vehicles surfaces ("vehicle" spills).

A photo of the ground surface below each refueling point was taken before refueling began and before the Service Professional laid the drip mat onto the ground, and another photo was taken after refueling concluded and after the drip mat was removed by the Service Professional. A senior Booster employer (Senior Operations Trainer, Learning & Development) from Booster facilitated this process and at times asked the Service Professional to delay refueling so that study personal had an opportunity to take the "before" photo.

In case of potential spills onto the ground, we were planning, similar to the CARB study, to analyze the imprints of the spills. For that purpose, we planned to take a photo of the imprint area of the spilled droplet together with a ruler laid next to it, such that later on the imprint area could be estimated from the photo. We note, however, that we, unlike the CARB study, did not spill on purpose known amounts of gasoline onto the ground surface of the refueling sites with the goal of determining a relationship between the unknown spill volume and the measured imprint area of the spilled droplet.

In addition, we assessed whether the Service Professionals followed the following Booster refueling procedures:

- Correct placement of the diaper at the tank inlet of customer vehicles, and

- Correct placement of the drip mat underneath tank inlet

Finally, we also ascertained our ability of detecting spillages on the ground surfaces present at the refueling sites. For that purpose, we dropped 0.5 mL of water from an about 1-m elevation onto the ground and then checked whether the droplet could be discerned upon hitting the surface. In addition, a photo was taken of the spillage location before and after spilling the droplet. We note that the 0.5 mL spill volume is less than the 1 mL spill volume, below which spills are not quantifiable according to CARB.

2.4. Spills captured by the diaper

Gasoline spills captured by the diaper during a mobile refueling event were determined through a mass balance approach. Immediately before individual refueling events, an unused diaper was pre-weighed at the refueling site, and the Service Professional then used this diaper for vehicle refueling. After vehicle refueling, the Service Professional returned the nozzle (with the diaper wrapped around it) to the tanker truck and handed the used diaper for post-weighing to research personnel.

To obtain a stable mass reading, an electronic balance (Bonvoisin Lab Scale, 3000 g range, 0.01 g accuracy) was placed in a windproof environment, which consisted of a large plastic bin that included a lid (see **Figure 1**). The bin and lid were transparent such that the display of the balance could be read from outside the closed bin. To avoid movement of the bin due to wind potentially causing unstable mass readings, a heavy paver was put horizontally into the bin, and the balance put on top of it. Since the diaper was bigger than the weighing pan of the balance, the diaper was folded and put into a tubber ware, with its lid being closed during the measurement. This approach prevented erroneous mass readings due to the diaper touching the walls or the lid of the large plastic bin.

Even though the diaper is oil-absorbing and water repellent, spilled gasoline that has been absorbed by the diaper can be released by the diaper to the atmospheric environment through the process of evaporation. The cumulative evaporative loss increases with time. Thus, the captured gasoline mass is underestimated when simply subtracting the post-refueling mass of the diaper from the pre-refueling mass. To adjust for these evaporative losses, we performed experiments in which we released gasoline masses with approximate weights of about 1 g or 20 g to clean diapers. We found that after 5 min, which is about the time between refueling events, one third (33%) of gasoline evaporated. Therefore, to adjust for the process of gasoline evaporation from the diaper, we multiplied the difference of the post-refueling and pre-refueling fuel mass by a factor of 3/2 = 1.5. We note that this adjusted mass is likely a conservative estimate, because it assumes that all gasoline is spilled into the diaper at the beginning of refueling. However, the CARB study has shown that the greatest spillage during refueling at gas stations occurs toward the end of refueling, during the shut-off phase (see Table 1).

Figure 1: Photo of the windproof environment, in which diapers potentially containing captured spilled gasoline were weighed.

3. Results

3.1. Ground spillage observations

Mobile refueling was carefully observed by study personnel at the refueling points in order to detect and document potential spills onto the ground. The Service Professional refueled vehicles following standard Booster procedures, except for the fact that the Service Professional was at times asked to delay refueling so that study personnel could take a photo of the ground surface below the refueling point before the drip mat was placed underneath the refueling point and before refueling began.

Thirty refueling events were observed at three different sites, and results are summarized in **Table 2**. Study personnel did not observe any spills onto the ground. **Figure 2** shows an example of photos of the ground below the refueling point before and after refueling. Like in all other refueling events examined, no spillages were observed below the refueling point.

Figure 2: The left and right photo show the ground below a refueling point before and after a mobile refueling event, respectively. No spills were observed during the 30 refueling events we examined.

Table 2: Summary of ground spillage observations below refueling points.

Site ID	# of refueling events	# of vehicle spills	# of ground spills	Percentage of ground spills
1	5	0	0	0%
2	14	0	0	0%
3	11	1	0	0%
All sites	30	1	0	0%

Study personnel observed one vehicle spill on the body of a van as evidenced by a shiny and smelly gasoline film on the body of the vehicle (see **Figure 3**). Quantifying the magnitude of the spill is difficult; however, we tried to estimate a conservative upper bound. We are confident that the vehicle spill was much smaller than the 1 mL, which CARB determined to be quantifiable (based on the imprints of gasoline droplets spilled onto concrete surfaces). This is because the volume of 1 mL of gasoline is easily discernable to the naked eye as this volume corresponds to a cube with side length of 10 mm. That vehicle spill did not result in a spill onto the ground. This is supported by the CARB study which found that about 1 to 3 mL of gasoline need to be spilled onto a vehicle's surface in order for them to drip onto the ground surface as a measurable spill.

Figure 3: Vehicle spill.

To verify that study personnel can discern potential gasoline spills onto the ground, 0.5 mL of water were spilled onto the ground of two out of three mobile refueling sites, where the spill study was conducted. **Figure A** in the Appendix demonstrates that the spilled water mass can clearly be discerned on the ground. On the gravelly surface, gravel pebbles get darker after the spill. On the grassy surface, leaves become shinier.

3.2. Spills captured by diaper

To determine the gasoline mass captured by the diaper, measurements for a total of 30 mobile refueling events at three sites were performed. The Service Professional refueled vehicles following standard Booster procedures, except for the fact that the Service Professional was asked to return the nozzle to the tanker truck after each refueling, where the diaper was replaced by an unused one.

Figure 4 and **Table 3** summarize the measurements. We estimate that on average 0.53 g of gasoline, which otherwise would have been spilled, were captured by the diaper. Therefore, as hypothesized, the captured spill mass during mobile refueling is smaller than the 2.9 g spill mass measured at self-service gas stations, and this difference is statistically significant (p = 2e-11).

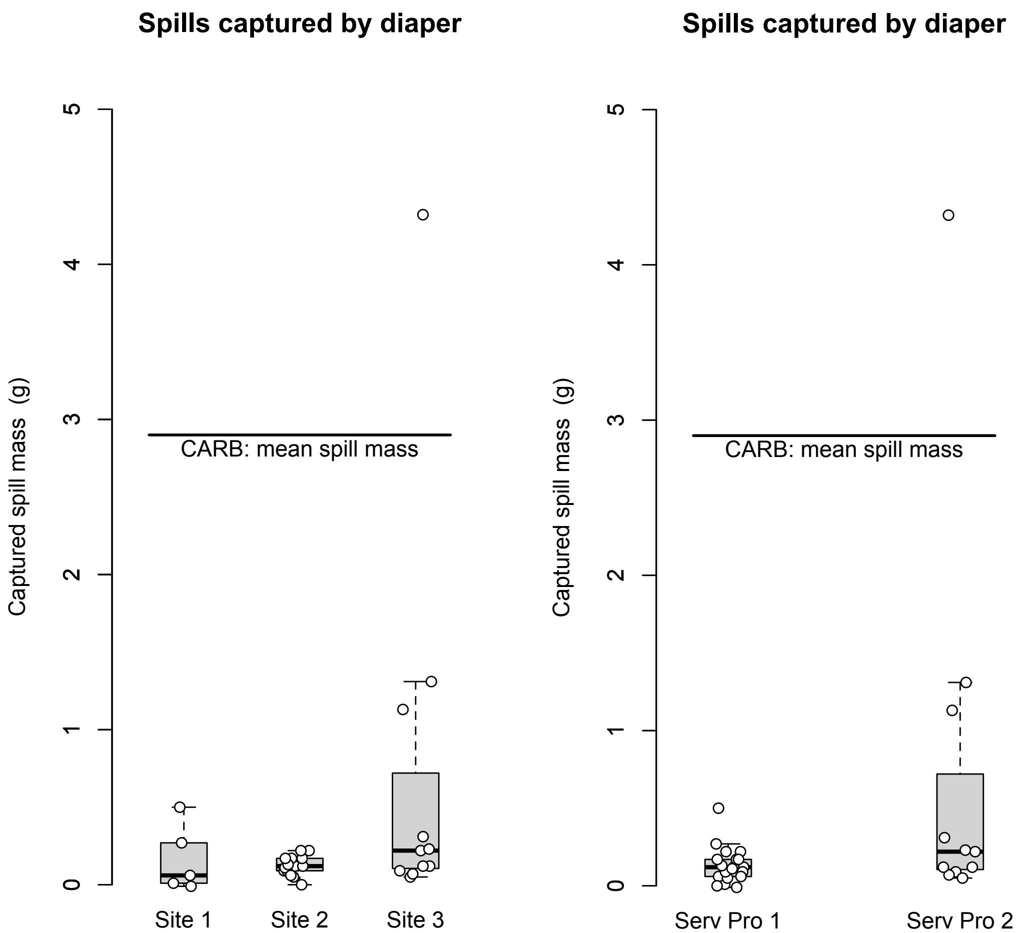


Figure 4: Box plots for spill mass captured by the diaper at three different mobile refueling sites (raw values, not adjusted for gasoline evaporation from the diaper). The boxes indicate the inter-quartile range (IQR).

Table 3: Mean (standard deviation) captured spill mass of all refueling events and stratified by site and Service Professional. Raw values refer to the post- and pre-refueling difference in diaper mass. Adjusted values account for gasoline evaporation from the diaper. The p-value corresponds to the hypothesis that the adjusted captured spill mass differs from the mean spill mass of 2.9 g measured by CARB.

	Raw captured spill mass (g)	Adjusted captured spill mass (g)	p-value
all refueling events	0.35 (0.81)	0.53 (1.20)	1e-11
by Site			
Site 1	0.17 (0.22)	0.25 (0.33)	0.00005
Site 2	0.12 (0.06)	0.18 (0.10)	2e-16
Site 3	0.72 (1.27)	1.09 (1.90)	0.01
by Service Professional			
Service Pro 1	0.13 (0.12)	0.20 (0.18)	2e-16
Service Pro 2	0.72 (1.27)	1.09 (1.90)	0.01

4. Conclusions and Discussion

No spills to the ground below refueling points were observed during the 30 mobile refueling events examined, which is consistent with our first hypothesis. This can be attributed to the use of an oil absorbing pad ("diaper"), which during nozzle transfer and mobile refueling is wrapped around the dispensing nozzle, and which captures gasoline that would otherwise be spilled onto the ground. The drip mat underneath the refueling point should serve as an additional fail-safe in case the diaper does not capture all spilled gasoline; however, we did not quantify potential spills captured by the drip mat, because the drip mat can accumulate materials other than spilled gasoline to a much greater extent than the diaper as the drip mat is laid onto the ground.

During one out of 30 refueling events examined we observed a gasoline film on the body of a customer vehicle. That spill, however, was much smaller than the vehicle spills defined by CARB and did not reach the ground surface.

Gasoline masses captured by the diaper were significantly smaller than the masses of gasoline spilled during refueling at traditional gas stations, which is consistent with our second hypothesis. The captured gasoline mass appears to depend on tanker truck refueling equipment or refueling personnel, or both.

The liquid gasoline mass captured by the diaper can be interpreted as a loss, i.e., gasoline that does not end up in vehicle tanks of customers. We found that the losses during mobile refueling were smaller than the refueling losses at regular gas stations. This can potentially be attributed to the fact that mobile refueling is performed by trained professionals. The smaller gasoline losses during mobile refueling are significant in two respects: 1) they represent a monetary benefit to the customer, and 2) they result in fewer air toxics emissions (via gradual gasoline evaporation from the diaper) when compared to regular gas stations (via evaporation of spilled gasoline).

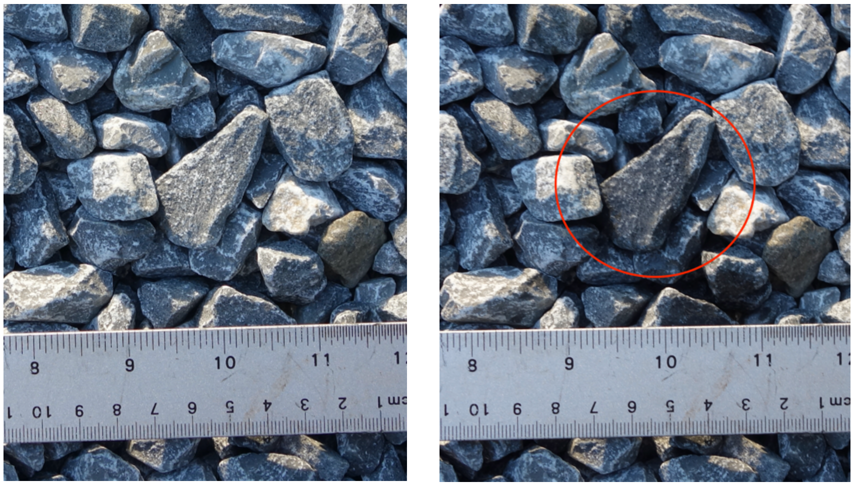
A limitation of our study is that only few Service Professionals were observed. Additional refueling events should be examined to understand better how tanker truck refueling equipment and refueling personnel affect the spill mass captured by the diaper.

Overall, the refueling procedures used during mobile refueling are commendable. Specifically use of a "diaper" wrapped around the nozzle, a drip mat below the refueling point, and no topping-off of vehicle tanks appear to reduce gasoline losses and associated releases to the environment. Diapers and drip mats used during mobile refueling could potentially also be used at gas stations with gas station attendants to minimize refueling spills.

References

Morgester, J. J., R. L. Fricker and G. H. Jordan (1992). "Comparison of spill frequencies and amounts at vapor recovery and conventional service stations in California." *Journal of the Air & Waste Management Association* 42(3): 284-289.

APPENDIX



(a)

(b)

(c)

Figure A: release of 0.5 mL water on (a/b) gravelly and (b) grassy surfaces.