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Onboard Refueling Vapor Recovery: Evaluation of the ORVR Program in the United States

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Introduction

This analysis focuses on the implementation of Onboard Refueling Vapor Recovery (ORVR) systems in the US and compares the pros and cons of using ORVR and Stage II controls to limit refueling emissions. ORVR and Stage II controls refer to emission control systems that capture fuel vapors during refueling. ORVR systems, as the name indicates, are incorporated into the vehicle, while Stage II vapor recovery equipment is incorporated into gasoline pumps at dispensing facilities.[1]

When the US Environmental Protection Agency (EPA) first considered control of refueling emissions in the 1970's, it looked into both ORVR systems and Stage II controls. Stage II controls can be implemented quickly: unlike ORVR, they do not require a full turnover of the vehicle fleet and they can be retrofitted. But Stage II controls require high capital investment costs as compared to ORVR devices, and are subject to deterioration from heavy use. Hence, Stage II controls require significant monitoring and maintenance to ensure emissions control efficiency. Also, area-wide efficiency drops if compliance waivers are granted for small throughput stations. ORVR devices lack some of the drawbacks of Stage II controls: they are highly efficient, require little maintenance, and are inexpensive on a per vehicle basis. ORVR controls, however, require a long implementation period because the devices cannot be retrofitted, and fleet-wide efficiency depends on the fleet turn-over rate.

Over the last ten years, ORVR has been successfully implemented in the US. A review of ORVR efficiency and penetration conducted by EPA demonstrated a high degree of efficiency and reliability on consumer owned vehicles, and showed that the system is highly cost effective (EPA, 2011a; EPA, 2011b). By adopting a dual ORVR/Stage II approach, requiring Stage II controls in severely polluted areas, and phasing in ORVR requirements for new vehicles starting in 1994, the US was able to take advantage of Stage II controls to quickly reduce VOC emissions in areas with severe pollution problems. The US

[1] Stage I control devices collect vapors given off during transfer from a delivery truck to a storage tank. For a general summary, see http://www.epa.ohio.gov/dapc/engineer/stgtc.aspx.

model also allowed time for ORVR devices to gradually penetrate the vehicle market, resulting in a more cost effective system that reliably mitigated refueling emissions in the long term.

Brief history of ORVR adoption in the US

The EPA adopted ORVR controls for light duty vehicles (LDVs) and light-duty trucks (LDTs) with a final regulation published in January 1994. The regulatory agency concluded that ORVR devices would prove more cost-effective and efficient than Stage II controls. The mandate was implemented in three-year phases, beginning with LDVs in 1998; lighter weight LDTs in 2001; and heavier LDTs in 2004.

The Clean Air Act of 1990 mandated the adoption of ORVR, but required continued use of Stage II controls in certain nonattainment areas until otherwise directed by the EPA Administrator. Once the EPA had determined that ORVR equipped vehicles were "widespread" enough within the overall vehicle fleet, it would allow the mandate for Stage II controls to be dropped. From that point forward, local officials would have discretion to continue using Stage II controls as necessary, but the previous federal mandates regarding Stage II devices would no longer apply.

On July 15, 2011, the EPA published a Notice of Proposed Rulemaking (NPRM) in the Federal Register that introduced a new estimate regarding ORVR systems. The EPA projected that sufficient fleet turnover to vehicles equipped with ORVR systems would occur by June 30, 2013, satisfying the "widespread" criterion of the Clean Air Act. This official proposal was based upon an analysis that concluded that ORVR systems were operating on average at 98% efficiency or greater. It also concluded that Stage II efficiency ranged from 62% (in areas with little or no enforcement) to a high of 92% (in areas with maximum enforcement). The EPA analysis used an average efficiency estimate of 86% and focused mainly on "nonattainment areas," i.e., areas with average levels of policy enforcement.

1. Reasons for Controlling Refueling Emissions

1.1. Overview

VOC emissions (or hydrocarbons), as ozone precursors, have long been an essential object of emission control strategies both for vehicles and non-vehicles within the US. Since the 1990s, vehicle emissions standards have increasingly focused on NOx reductions. Control of VOC emissions, however, has remained a relatively constant priority throughout the years. VOC emissions contribute greatly to ozone formation, and represent a major fraction of direct toxic emissions. Of particular concern are the VOCs emitted during refueling; gasoline vapor contains benzene, a potent human carcinogen, and other toxics like toluene and xylene.

In clear and sunny conditions, VOCs react with NOx to form tropospheric ozone in a reaction that is driven by complex photochemistry. Depending on the ratio of NOx to VOCs, regions can be generally divided into "VOC-limited" or "NOx-limited". At a low VOCs/NOx ratio, ozone formation is limited by the amount of VOCs available for the chemical reaction. Under this "VOC-limited" situation, reducing VOCs can effectively lower ozone concentration. In "NOx-limited" regions where typically the VOCs/NOx ratio is high, ozone formation is controlled by NOx concentration. Hence, in these regions, NOx control measures are more effective in lowering ozone concentration (Sillman, 1999).

1.2. Contribution of Refueling Emissions to Total VOC Inventory in the US

Refueling emissions contribute a significant fraction of overall mobile source VOC inventories. Had refueling emissions never been controlled, this source would have become one of the largest portions of the LDV/LDT VOC inventory given the continued lowering of exhaust emissions standards for this sector.

(a) The US EPA's ORVR final rulemaking documentation (EPA, 1994a, 1994b) estimated total refueling emission (prior to control) to be 475,000 tons per year, of which 200,000 tons per year occurred during the critical five month ozone season.

(b) To place this in perspective with the total LDV/LDT inventory, it is useful to compare refueling emissions to exhaust emissions on the same basis (in grams/mile).

- Uncontrolled refueling emissions were estimated at 0.2 grams per mile for LDV/LDTs, based upon typical fuel consumption characteristics and the amount of fuel dispensed by these vehicles during the early to mid 1990s (EPA, 1994a).
- Full useful life exhaust emissions standards for non-methane hydrocarbons were estimated at 0.3 to 0.4 grams/mile when ORVR controls were first implemented. Exhaust emission standards were gradually lowered via various phase-in steps to an average of approximately 0.09 grams/mile under the current EPA "Tier 2" standards. EPA's "Tier 3" and California's "LEV III" standards, currently in the development stage, are projected to further reduce exhaust emission standards to an average of 0.01 grams/mile by 2025. [NOTE: California held several public workshops regarding LEV III plans and indicated that it plans to adopt the standards at a board hearing scheduled for November 2011. EPA recently announced its intent to adopt Tier 3 standards, which are greatly harmonized with the California LEV III standards. Both packages would further reduce exhaust and evaporative emissions standards.][2]

1.3. Contribution of Refueling Emissions to Total VOC Inventory in Europe

A 2005 consultant report, developed by ENTEC for DG-Environment, estimated that the quantity of VOC emissions caused by gasoline refueling in the EU and Croatia will reach 87.2 kilotons by 2010 (Entec UK Limited, 2005). This figure represents about 1% of total emissions of anthropogenic VOC emissions in 2005 (9006 kilotons).[3] New EU legislation requires an increased quantity of ethanol in gasoline, which suggests that some member states may

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[2] For more details about the LEV III and Tier 3 standard development, see EPA websites: http://yosemite.epa.gov/opei/rulegate.nsf/byRIN/2060-AQ86 and http://www.epa.gov/improvingregulations/vehicleregulations.html, and ARB website: http://www.arb.ca.gov/msprog/levprog/leviii/leviii.htm.

[3] See Table 1.1 and Table 6.3 of Entec UK Limited (2005).

opt for higher vapor pressure limits for gasoline blended with ethanol. If the regulated vapor pressure is increased from 60 kPa to 70 kPa, the VOC emissions from refueling will increase to 90.5 kilotons. Though the contribution of refueling emissions appears low, it should be noted that nearly half of the fleet in the EU uses diesel fuel.

2. Estimates for Reduction of Refueling Emissions

2.1. US Estimates for VOC Reduction Due to ORVR

EPA's rulemaking documentation associated with its 1994 ORVR final rulemaking package projected an average efficiency for ORVR of 95%. However, extensive testing of in-use vehicles has demonstrated a fleet efficiency of approximately 98% (EPA, 2011b).

(a) The rulemaking projected a range of efficiencies associated with varying inspection/maintenance (I/M) impacts across the county. However, in-use testing has demonstrated excellent system durability over a vehicle's useful life with almost no special maintenance needs. Hence the variation projected to result from I/M differences has turned out to be minimal.

(b) Actual experience has shown that carbon canisters used by manufacturers have tended to be larger than necessary. Larger canisters are used to create an extra compliance margin. Modern manufacturing techniques make it possible to design oddly shaped canisters that can minimize space constraints when installing large canisters.

(c) The above estimates of ORVR efficiency are based on testing of vehicles using the full test procedure, which includes a 90% fuel fill. In the real world, systems are not often stressed to this extreme, as it has been found that consumers typically refuel long before reaching the 90% empty level.

2.2. US Estimates for VOC Reductions Due to Stage II

While optimized Stage II systems can achieve 95% efficiency, deterioration, lack of maintenance, and insufficient inspection/enforcement leads to a lower average efficiency. An overall efficiency of about 70% has been estimated, with performance in the range of 62% to 92% (EPA, 2004; EPA, 2011b).

(a) EPA state implementation plan (SIP) guidance estimates that 92% efficiency can be achieved with semi-annual inspection and strong follow up enforcement.

(b) Annual inspection is estimated to result in 86% efficiency.

(c) Minimal inspection is estimated to result in 62% efficiency.

(d) These average efficiency levels apply only to the gas stations that have Stage II controls applied. Under current regulations, stations with a throughput of 10,000 gallons per month or less are exempt from Stage II controls due to the high cost of installation. If these stations are included in efficiency estimates, it leads to lower projections for overall Stage II effectiveness in an entire control region. It has been estimated that the lower end projection of 62% efficiency (as seen above) decreases to approximately 56% when calculated on a region-wide basis that includes stations exempt from control.

(e) When the "widespread" analysis noted above was performed, the balancing point at which the ORVR fleet would be large enough to result in the same level of control as that being achieved by Stage II controls in typical nonattainment areas was computed using an assumed efficiency of 86%. This was the estimated average efficiency of Stage II systems installed in average nonattainment areas. The analysis then discounted this level to allow for the fact that not all stations would be required to have Stage II controls.

2.3. Impact of ORVR/Stage II Compatibility Issues

A compatibility issue arises when ORVR vehicles are refueled at stations equipped with Stage II controls. The compatibility problem is associated with "breathing losses" at service station tanks. This issue was addressed at the recent EPA NPRM discussions on the "widespread" issue (EPA, 2011b). The EPA NPRM concluded that the incompatibility issue could result in a 1% to 10% lower efficiency than could be achieved by ORVR or Stage II alone. The higher end of the range (10%) was calculated using certain Stage II designs that rely upon a high amount of vacuum assist.

(a) The following is an excerpt from the EPA preamble discussing the incompatibility issue:

"When an ORVR vehicle is fueled at a service station equipped with a vacuum assist Stage II vapor recovery system, a lack of compatibility between the two controls may actually cause the emission reduction of the two systems together to be less than the emission reduction achieved by either system alone. The problem arises when the ORVR canister captures the gasoline emissions from the motor vehicle fuel tank. Instead of drawing vapor-laden air from the vehicle fuel tank into the underground storage tank, the vacuum pump of the Stage II system draws fresh air into the underground storage tank. The fresh air causes gasoline in the underground tank to evaporate inside the underground tank and thus creates an increase in pressure in the underground storage tank. As a result, gasoline vapors may be forced out of the underground storage tank vent pipe into the ambient air. This incompatibility can result in a 1 to 10 percent decrease in control efficiency over what would be achieved by either Stage II or ORVR alone. The decrease in efficiency varies depending on the vacuum assist technology design (including the ratio of volume of air drawn into the underground tank compared to the volume of gasoline dispensed), the gasoline Reid vapor pressure, the air and gasoline temperatures, and the fraction of throughput dispensed to ORVR vehicles. There are various technologies that address this incompatibility, such as nozzles that sense when fresh air is being drawn into the underground storage tank and stop the air flow. Another solution is the addition of processors on the underground storage tank vent pipe that capture or destroy the gasoline vapor emissions from the vent pipe. Installing these technologies adds to the expense of the control systems and is in some cases a reason to remove Stage II systems." (EPA, 2011b)

(b) This incompatibility will be one of several considerations for local/regional authorities deciding whether to continue using Stage II controls after the federal mandate for their use is dropped. The question is also relevant to cities and regions that have already begun to transition from Stage II to nationwide ORVR controls. While this incompatibility can subtract slightly from the efficiency of ORVR systems, consideration of this loss must be weighed against the possible benefits of continuing Stage II controls. Examples of potential benefits from maintaining Stage II controls include:

- The control of refueling emissions from pre-ORVR vehicles for as long as such vehicles exist in the fleet.
- The control of refueling emissions from heavy-duty vehicles that have not been subjected to ORVR requirements.

2.4. Status of European Evaporative Test Procedures

Europe's focus has historically been on NOx and PM reductions, in part because their fleet is nearly 50% diesels. Europe introduced stricter evaporative controls with Euro 3 in 2000.

(a) The current European evaporative emission procedure does not involve multiple day diurnal simulations as does the US procedure. The current Euro procedure is similar to the prior US procedure (i.e., the one that pre-dated the current 2-day and 3-day tests) that was adopted in 1993. The full evaporative emission test consists of a 1-hour hot soak test plus a 24-hour diurnal test with a limit of 2 grams/test.

(b) Europe is currently considering revisions to their evaporative test procedure to make it more representative of "real driving conditions." Instead of inventing something new, Europe may choose to adopt one or more of the US multi-day tests with some modifications (conditioning cycle, canister conditioning procedure, etc.). A 48-hour diurnal test combined with a more aggressive purging strategy (forced by reducing the current available purging time) seems to be the option delivering the largest benefits. Current focus is on changing the evap test procedure but not the standard. [NOTE: Changing the test procedure to include multiple day diurnal emissions (as the US did in 1993) would cause significant emissions reductions even if the numerical standard in terms of grams per test was not changed]. Fuel permeation (increased with ethanol) and durability of evaporative emission control systems are also being addressed (the new certification procedure might include elements to address these issues).

(c) The EU Joint Research Center is studying the potential impacts and benefits of revising the evaporative test procedure. Along with this, they are also studying ORVR issues, including overall cost and cost effectiveness. They have said that they are considering all of the information available in the US. They are aware of the US EPA conclusion that ORVR is more efficient and cost effective than Stage II.[4]

(d) Europe's currently reported goal is to have a proposal for revised evaporative test procedures, and perhaps revised standards by mid-2012.

(e) Euro 6 is scheduled to go into effect in 2014; it appears unlikely that revised evaporative requirements, with or without ORVR, will be implemented with the initial start up of Euro 6. A recent proposal of the Commission on the particle number limit for petrol vehicles

[4] Communications with Giorgio Martini of the Joint Research Center of European Commission, June 29, 2010.

introduces a further regulatory step after Euro 6 (a first relaxed PN limit will enter into force in 2014 while a more stringent standard will be implemented in 2017). The revised evaporative emission procedure might follow the same approach.

(f) To date, Europe has treated the problem of refueling emissions as a local issue; it was believed that areas in need of additional VOC control would implement Stage II. While some member states have already required the introduction of Stage II systems at the national level, Stage II controls were not widely implemented yet. There is not much information available regarding the effectiveness of Stage II systems in Europe. In 2009, a new EU directive (2009/126/EC) was adopted that mandated "the installation of Stage II petrol vapor recovery equipment at i) new and refurbished stations above 500m^3 throughput per annum of petrol; (ii) retrofitting of existing stations with a throughput above 3000 m^3 by 2018; and (iii) all new or substantially refurbished stations situated under residential accommodation to equip with Stage II controls irrespective of size; (iv) no obligation to install automatic monitoring of Stage II [petro vapor recovery] equipment but permit a longer period between inspections if it is installed" (European Council, 2009). The Member States have until December 31, 2011 to turn the Directive into national law. However, the cost/benefit analysis carried out at the time did not include the ORVR option which was early discarded, mainly due to the long time needed to achieve significant air quality benefits.

3. Policy Options – Stage II vs. ORVR

3.1. General Review of Pros and Cons of ORVR and Stage II

(a) Stage II

- Pros
  - Can be implemented more quickly (not subject to fleet turn-over time) since controls can essentially be retrofitted onto existing service stations.
  - Can focus on regional implementation in areas of high need.

- Cons
  - Effective local approval and system installations oversight is needed.
  - Significant monitoring and maintenance are needed since components of the refueling interface (nozzles, nozzle boots, and hoses) are subject to deterioration from use. EPA estimates that systems with a designed efficiency capability of 90% to 95% actually function in the range of 62% to 92%, depending on the degree of oversight.
  - Area-wide efficiency drops further if compliance waivers are granted (as has occurred in the US) for small throughput service stations.
  - The retrofit advantage comes at a high capital cost investment, and expensive continued maintenance is required.

(b) ORVR

- Pros
  - High efficiency – US EPA estimates 98% on a per vehicle basis.
  - Needs little maintenance; in-use testing has indicated little deterioration over useful life.
  - Inexpensive per vehicle cost; highly cost effective.
- Cons
  - Long implementation time due to slow fleet turn over; retrofitting is not a practical option.
  - Needs effective certification testing and approval.
  - There may be some in-use conditions where the canister purge system could be overwhelmed with high vapor volumes. Test procedures need to consider extreme rather than average or typical conditions.

3.2. Why US Chose ORVR and Overview of US ORVR Program Results

The US chose ORVR because of its high efficiency, cost effectiveness, and ability to function without significant monitoring or maintenance. Additionally, the ORVR technology could easily be integrated with enhanced evaporative emission control systems already in place. The primary disadvantage of ORVR was mitigated by the implementation of Stage II controls in nonattainment areas where maximum VOC control was needed most quickly. As discussed earlier in this analysis, the results of the use of ORVR (which began in 1998) have been favorable; ORVR systems are operating at higher efficiency than originally projected.

(a) The US regulations permit both systems that are integrated with evaporative emissions systems and systems that are not integrated. "Integrated" essentially means that one carbon canister and vapor purging system controls both evaporative and refueling vapor emissions. Non-integrated systems involve a separate canister and purge system; vapors are only directed to the canister during refueling.

- The US has stringent evaporative emissions standards and test procedures that require both large carbon canisters and aggressive purge strategies. Due to these pre-existing regulations, manufacturers primarily use integrated systems. Only in very rare instances is it preferable to use non-integrated systems.
- The evaporative emissions regulations implemented two test procedures. Manufacturers had to design control systems that could pass the standards under both procedures.
    - One test involved a two-day diurnal heat build temperature cycle. This test required a very aggressive purge strategy as the test allowed only a minimal driving period for the system to create enough capacity in the carbon canister to be able to contain vapors from the two-day diurnal test period.
    - As a result, the <u>2-day procedure tends to dictate the design purge conditions</u> for the vehicle.
    - The other test involved a three-day diurnal. The <u>3-day test tends to drive the size of the canister</u> needed. On a relative basis, the purge conditions required under the three-day test were less stringent than on the two-day test.

- When the ORVR requirements were added on, it was determined that the large canisters required by the three-day evaporative emissions test would be large enough to also handle the control of refueling emissions.
- Hence, EPA concluded that it was unnecessary to include additional canister cost in the overall cost estimate for ORVR systems. This conclusion was realistic; manufacturers generally implemented ORVR controls without need of canisters larger than those previously adopted for evaporative emissions compliance.
- Non-integrated systems are advantageous primarily in cases where the manufacturer has difficulty achieving high purge rates. In theory, non-integrated systems allow for lower rates purge rates because the canister only has to be purged fast enough to create enough canister capacity to handle the next refueling event. However, in the US, rapid purge capability is necessary in order to handle evaporative emissions. Thus, having a separate system solely for refueling vapor control provides no advantage.

(b) In its final rulemaking, EPA estimated the cost of ORVR to be $6 to $8 (in USD, at 1992/1993 rates).

- As explained above, this was the incremental cost of the system without any added cost for increased canister size.
- This included the cost of R&D, which EPA assumed would be amortized over a period of 5 years. The remaining cost came from hardware associated with enlarged vapor lines and an enlarged rollover valve (necessary to accommodate the rapid flow of vapors during refueling).
- EPA projected that fuel savings would entirely offset the cost of the system over the long term if Stage II controls were eventually eliminated and the cost of fuel saved could be attributed fully to ORVR.
- Since Stage II controls were already in place at the time of the rulemaking, the only fuel savings included in the cost estimate were the incremental savings that exceeded those of Stage II (i.e., the incremental savings due to ORVR's higher efficiency and

wide-spread implementation, as compared to Stage II controls). The reduced fuel savings estimate was $2 to $4 dollars, yielding a net ORVR system cost of under $5.

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APPENDIX: Simplistic Overview of the US EPA ORVR Test Procedure

Refueling (same for integrated and nonintegrated):

- Disconnect vapor line to canister
- Drain fuel tank and fill with refueling test fuel to 10% capacity
- Soak 6 to 24 hours at 80 ± 3 F (26.7 ± 1.7 C)
- Reconnect line
- Perform refueling test in an evaporative measurement SHED
- Dispense fuel at 4 to 10 gpm (15.1 to 37.9 liters per minute) and terminate at the first auto shut off that occurs once at least 85 percent of nominal capacity has been pumped
- The dispensed fuel temperature must be 67 ±1.5°F (19.4 ± .8 C) and tank at the 80°F F (26.7°C) soak temp
- Dispensed fuel shall have an RVP of 9.0

Precondition an integrated system:

- Drain tank and fill to 40%
- Soak 12 to 36 hours at 68 to 86°F (20 to 30°C)
- Precondition drive over one UDDS cycle
- Again drain and fill to 40%
- Precondition canister
  - Precondition with 50/50 mixture of butane and nitrogen at rate of 40 grams butane per hour until 2 grams breakthrough, or
  - Load canister to breakthrough with gasoline vapors by conducting repeated diurnal heat builds
- Run exhaust emissions test
- Now refueling test departs from the evaporative test
  - Additional driving of one UDDS cycle followed by a New York city cycle followed by one more UDDS
- Ready to do refuel test

Precondition a nonintegrated system:

- Just drive UDDSs until 85 percent of fuel consumed
- EPA can do a partial test – drive until x% fuel used and then do an x% refuel test

Fill Pipe Seal Test

- Just to check fill pipe seal
- Purge canister so no evap emissions
- No prep driving
- Do refuel test – if fails test it has to be because of seal